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Distributed Energy Resources:
a new asset for ancillary services market

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To someone that will be very special...

Acknowledgments

Ricordo le parole di un mio carissimo professore: «Ragazzi, anche se il vostro percorso vi porta spesso a ragionare in maniera tecnica e razionale, non dimenticatevi mai del lato umano delle persone». É per questo che ci tengo a ringraziare in particolar modo Lorenzo ed Enrico, che mi hanno seguito nello sviluppo di questo lavoro sin dal principio. Oltre a supportarmi dal punto di vista professionale, si sono rivelate persone con un grande lato umano, riuscendo a sostenermi nei momenti più difficili, senza mai farmi perdere di vista l'obbiettivo finale. Un grazie anche al professor Cristian Bovo, per i suoi preziosi consigli durante lo sviluppo di questa tesi. Ringrazio anche tutte le persone che ho avuto modo di conoscere in ENGIE E.P.S e che, ciascuna a proprio modo, hanno reso piacevole e stimolante questa esperienza. Voglio poi spendere alcune parole per ringraziare Alessandro, Guido, Massimo e Sergio, con cui ho avuto il piacere di condividere questi mesi in azienda, senza dimenticare tutti i compagni di corso con cui ho trascorso questi ultimi cinque anni universitari.

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Abstract

This thesis can be framed in the Italian electricity market scenario, which is facing deep changes both from a technical and a regulatory point of view. Ancillary services market has been considered as the main topic for this final dissertation, pointing out how its behaviour results strictly related with the increasing penetration of renewable energy sources. In this context, after the emission of the decree 300/2017/R/eel, various pilot projects have been introduced, deeply analysing the virtual enabled mixed unit (UVAM, Unità Virtuale Abilitata Mista) and its applications.

This analysis considers an aggregate, representing a UVAM, constituted by 3000 residential units and a commercial one. These units are coordinated by a new market figure, namely the aggregator. The present work analysis the potentialities that these new players can introduce in the balancing market. These new resources are generally identified as Distributed Energy Resources (DERs); they can be alternatively generators, loads or storage systems. In this work, each residential unit has been considered enabled to install a solar power plant, an energy storage system, a controllable dish-washer, a controllable washing-machine and a controllable air-conditioner. On the other hand, the commercial unit, has a controllable air-conditioning system installed. The potential of the DERs is given by their power flexibility, provided through load shifting of dish-washer and washing-machine, load modulation of the air-conditioner and smart management of the energy storage system. To compute an economical estimation of the benefits introduced by these new resources, prices of the historical offers presented in the balancing market have been analyzed. Particularly, in order to associate to each offer, submitted at a given price, a certain probability of being accepted in the market, a market-analysis tool has been developed using MATLAB software. Then, adopting the same software, two optimization algorithms have been implemented. The first one maximizes the incomes that can be achieved by the aggregator on the balancing market. According to the results obtained from the market analysis and to other specific problem constraints, the model will provide the bidding power quantity, the bidding time and the scheduling of the flexible devices. The second one, instead, focuses on minimizing the costs in order to accomplish a predefined dispatching order, pointing out the different flexibility contributes and capabilities of residential and commercial units.

The final results can be grouped in two main categories: the ones obtained from the market-analysis and those assessed by the optimization algorithms. Even if the analysis of the balancing market was intended to provide input data for the optimization algorithms, also some considerations on the historical registered prices have been done. Relatively to 2017 balancing market, a general trend for the accepted offer prices could be identified: they were higher during colder months and, generally, during weekly days with respect to holidays. Moreover, comparing different market zones behaviours, it has been shown how North market zone is characterized by a higher number of accepted offers with respect to the others. Concerning the optimization algorithms, their results confirm that DERs can effectively be exploited for balancing market purpose, allowing relevant power modulation. From an economical point of view, the generated profits have been redistributed among the aggregator and the different units, both residential and commercial. Due to the considered assumptions and scenarios, which are quite premature for the current Italian market structure, the economics of the studied case are not very profitable. In any case, large improvement margins are still exploitable, and the unstoppable dynamics that are changing the electricity market structure will surely involve these new resources, leading to regulatory documents review in order to increase the technical and economic feasibility of these projects.

Sommario

Il presente lavoro di tesi è figlio dei recenti e profondi cambiamenti che stanno interessando la struttura del mercato elettrico Italiano. È stato evidenziato lo stretto legame esistente tra la diffusione delle cosiddette risorse energetiche distribuite (DER), in particolare le piccole unità di produzione a fonti rinnovabili, e le criticità che il mercato dei servizi di dispacciamento Italiano si trova a dover affrontare. In questo contesto, l'emanazione della delibera 300/2017/R/eel segna un mutamento radicale, abilitando alla partecipazione al mercato dei servizi ancillari un vasto panorama di utenti, precedentemente esclusi. Punto focale di questa delibera è stato l'approvazione di alcuni progetti pilota, dei quali è stato preso in esame quello denominato UVAM, Unità Virtuale Abilitata Mista. L'analisi condotta ha preso in esame un aggregato di utenze costituito da 3000 unità residenziali e da un'unità commerciale. Queste unità si interfacciano con un nuovo agente di mercato, denominato aggregatore, il quale ha il compito di coordinare la flessibilità offerta da ciascuna di esse. Con il termine flessibilità, si fa riferimento alla possibilità, da parte dell'aggregatore, di agire in maniera diretta su alcuni dispositivi degli utenti, definiti nel seguito controllabili. In questo lavoro, le utenze residenziali possono abilitare al controllo alcuni elettrodomestici tra cui la lavatrice e la lavastoviglie, un climatizzatore ed, infine, un sistema di accumulo elettrico. Per quanto riguarda l'utenza commerciale, essa abilita al controllo solamente il sistema di climatizzazione. L'aggregatore è incaricato di gestire la flessibilità fornita da ciascuna utenza, con l'obbiettivo di trovare una strategia efficace per offrire servizi di dispacciamento. L'analisi delle potenzialità di questo aggregato viene svolta seguendo una logica a cascata. Come primo passo, è stata condotta un'analisi economica sul mercato dei servizi di dispacciamento per l'anno 2017, in particolare sono stati analizzati i prezzi delle offerte accettate sul mercato del bilanciamento, ricavando una relazione tra essi e la probabilità di accettazione sul mercato. Successivamente, utilizzando i dati di mercato analizzati, due algoritmi di ottimizzazione sono stati sviluppati: il primo con l'obbiettivo di trovare quali siano il periodo della giornata, il livello di potenza e la configurazione dei dispositivi controllabili che massimizzano i ricavi dovuti dalla partecipazione al mercato dei servizi di dispacciamento; il secondo con l'obbiettivo di trovare la configurazione dei dispositivi più economica, sottolineando i diversi contributi forniti dalle utenze

residenziali rispetto a quelle commerciali, per rispettare un ordine di dispacciamento predefinito. Per quanto riguarda i risultati ottenuti, due contributi principali possono essere distinti. Il primo fa riferimento ai risultati ottenuti dall'analisi di mercato, il secondo, invece, si focalizza sui risultati ottenuti dai problemi di ottimizzazione. Per quanto riguarda l'analisi di mercato, oltre ai dati che correlano prezzi e probabilità di accettazione, è stato possibile osservare come nei mesi invernali, rispetto a quelli estivi, i prezzi sul mercato del bilanciamento registrati risultino maggiori. Stesso comportamento si registra confrontando i prezzi infra-settimanali con quelli del fine settimana. Focalizzando l'attenzione sui risultati ottenuti dalle simulazioni degli algoritmi di ottimizzazione, da un punto di vista teorico, è possibile provare l'efficace ruolo ricoperto da queste nuove risorse di dispacciamento nel fornire servizi di bilanciamento nel mercato elettrico. Volendo trarre delle conclusioni economiche, i risultati non risultano essere di primo impatto promettenti. Tuttavia, è importante tenere in considerazione quelle che sono state le diverse ipotesi di studio formulate, non tralasciando il fatto che questo genere di applicazioni è alquanto prematuro se paragonato all'attuale struttura del mercato Italiano. Per concludere, è importante prendere coscienza di come le diverse problematiche che stanno inficiando il sistema elettrico nazionale risulteranno essere sempre più influenti. Sarà quindi fondamentale adeguare il mercato elettrico da un punto di vista tecnico e regolatorio, facendo in modo che queste nuove tipologie di risorse flessibili possano trovare sempre più conveniente il loro ingresso nel sistema.

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Chapter 1

k: market zone k;

P_{min}: minimum power variation;

p_z: zonal equilibrium price;

Q_i^k: energy quantity purchased in the area k by user i;

$t_{max,1}$: maximum time that can elapse between a variation request and its application;

$t_{max,2}$: maximum time in which a minimum power variation (P_{min}) has to be guaranteed;

Chapter 3

$d.f.r$: daily fixed remuneration;

$fixed\_remuneration$: fixed remuneration for MB participation, achievable according to regulatory documents;

Nm: numbers of weekly days in a month;

Chapter 5

$\alpha_{agg_{ab}}$: binary value for the aggregator constraints definition;

$\alpha_{agg_{in}}$: binary value for the aggregator constraints definition;

α_{grid-c}: binary value for the commercial energy grid accounting for power injection or absorption;

α_{i-ess}: binary value of i-user energy storage system accounting for charging and discharging operation;

α_{i-grid}: binary value of i-user grid accounting for power injection or absorption;

α_i^{SD}: binary variable used for load shifting constraints definition, it is defined for shiftable loads, specified by apex "SD" of user i;

γ_i^{SD}:binary variable used for load shifting constraints definition, it is defined for shiftable loads, specified by apex "SD" of user i;

$\Delta^{AC}_{i-max_{ab}}$: maximum power injection increase with respect to reference profile for shiftable load "SD" of user i;

$\Delta^{AC}_{i-max_{in}}$: maximum power absorption increase with respect to reference profile for shiftable load "SD" of user i;

$\Delta^{ess}_{i-max_{in}}$: maximum power injection increase with respect to the reference profile for ESS of residential user i;

$\Delta^{ess}_{i-max_{ab}}$: maximum power absorption increase with respect to the reference profile for ESS of residential user i;

$\Delta^{grid}_{i-max_{in}}$: maximum power injection increase with respect to the reference profile of the grid of user i;

$\Delta^{grid}_{i-max_{ab}}$: maximum power absorption increase with respect to the reference profile of the grid of residential user i;

$\Delta^{DEVICE}_{i-max_{in}}$: maximum injection variation allowed for a certain device, specified by apex "DEVICE", with respect to its reference profile for user i;

$\Delta^{DEVICE}_{i-max_{ab}}$: maximum absorption variation allowed for a certain device, specified by apex "DEVICE", with respect to its reference profile for user i;

$\Delta P^{SD}_{i-max_{in}}$: maximum power injection increase with respect to reference profile for shiftable load "SD" of user i;

$\Delta P^{SD}_{i-max_{ab}}$: maximum power absorption increase with respect to reference profile for shiftable load "SD" of user i;

$\Delta^{AC}_{max_{ab}-c}$: maximum power absorption increase with respect to the reference profile of the air-conditioner of the commercial unit;

$\Delta^{AC}_{max_{in}-c}$: maximum power injection increase with respect to the reference profile of the air-conditioner of the commercial unit;

$\Delta^{agg}_{max_{ab}}$: maximum power absorption increase with respect to the reference profile of the aggregator;

$\Delta^{agg}_{max_{in}}$: maximum power injection increase with respect to the reference profile of the aggregator;

$\Delta^{grid}_{max_{ab}-c}$: maximum power absorption increase with respect to the reference profile of the grid of the commercial unit;

$\Delta^{grid}_{max_{in}-c}$: maximum power injection increase with respect to the reference profile of the grid of the commercial unit;

Δ_{min}: minimum time variation required by GME for MSD participation, it equals 4 hours;

$\varphi(k)$: binary value for the aggregator constraints definition;

ϕ_i^{SD}:binary variable used for load shifting constraints definition, it is defined for shiftable loads, specified by apex "SD" of user i;

η_c: charging efficiency of the ESS;

η_d: discharging efficiency of the ESS;

η_{load}: load line efficiency;

η_{pv}: solar plant efficiency;

$A_{incomes}$: aggregator incomes due to MB participation;

$a.p$: acceptance probability of the submitted offer;

C_{ab}: price of the electrical energy that the retailer pays to the user in MGP;

C_{in}: price of the electrical energy that a user has to pay to its energy retailer in MGP;

$C_{incomes}$: commercial unit incomes due to MB participation;

C_{MB}: balancing market prices;

$delay$: maximum time of which the air-conditioner cycle duration can be anticipated and postponed for a residential unit;

$delta^{DW}$: cycle duration time of the dish-washer;

$delta^{SD}$: shifting time of shiftable load specified by apex "SD" of user i;

$delta^{WM}$: cycle duration time of the washing-machine;

$DEVICE$: it can equals: PV, ESS, DW, WM or AC;

$dP_{i-grid_{in}}$: power injection variation with respect to the reference profile of the grid of residential user i;

$dP_{i-grid_{ab}}$: power absorption variation with respect to the reference profile of the grid of residential user i;

$dP_{i-ess_{in}}$: power injection variation with respect to the reference profile of the ESS at common node terminals of residential user i;

$dP_{i-ess_{ab}}$: power absorption variation with respect to the reference profile of the ESS at common node terminals of residential user i;

dP^{AC}_{i-load}: power variation with respect to the reference profile of the air-conditioner of user i, at common node;

dP'^{AC}_{i-load}: power variation with respect to the reference profile of the air-conditioner of user i, at AC terminals;

dP^{AC}_{load-c}: load power profile variation with respect to the reference profile of the commercial unit;

dP^{DW}_{i-load}: power profile variation with respect to the reference profile of the dish-washer of residential user i;

dP^{WM}_{i-load}: power profile variation with respect to the reference profile of the washing-machine of residential user i;

dP^{SD}_{i-load}: power variation with respect to the reference profile of the shiftable load specified by apex "SD" of user i, at common node;

${dP'_{i-load}}^{SD}$: power variation with respect to the reference profile of the shiftable load specified by apex "SD" of user i, at load terminals;

$dP^{SD}_{i-load_{in}}$: power injection variation with respect to the reference profile of the shiftable load specified by apex "SD" of user i, at common node;

$dP^{SD}_{i-load_{ab}}$: power absorption variation with respect to the reference profile of the shiftable load specified by apex "SD" of user i, at common node;

$dP'_{i-ess_{in}}$: power injection variation with respect to the reference profile of the ESS at battery terminals of residential user i;

$dP'_{i-ess_{ab}}$: power absorption variation with respect to the reference profile of the ESS at battery terminals of residential user i;

${dP'_{i-load_{in}}}^{SD}$: power injection variation with respect to the reference profile of the shiftable load specified by apex "SD" of user i, at load terminals;

${dP'_{i-load_{ab}}}^{SD}$: power absorption variation with respect to the reference profile of the shiftable load specified by apex "SD" of user i, at load terminals;

dP^{SD}_{i-load}: power profile variation with respect to the reference profile of the shiftable load "SD" of user i;

$dP_{grid_{in}-c}$: grid power injection variation with respect to its reference profile for the commercial unit;

$dP_{grid_{ab}-c}$: grid power absorption variation with respect to the reference profile for the commercial unit;

$dP_{agg_{in}}$: power injection variation with respect to the reference profile of the aggregator;

$dP_{agg_{ab}}$: power absorption variation with respect to the reference profile of the aggregator;

$dP^{1}_{agg_{in}}$: adopted for the formulation of the objective function, it equals $dP_{agg_{in}}$ only outside the MB participation interval, while, inside, it results zero;

$dP^{2}_{agg_{in}}$: adopted for the formulation of the objective function, it equals $dP_{agg_{in}}$ only during a dispatching order execution;

E_{ess_n}: nominal energy of the storage system for a residential user;

GME_{start}: start time for the execution of a dispatching order;

GME_{end}: end time for the ending of a dispatching order;

$GME^{in}_{quantity}$: power quantity relative to a dispatching order;

h: time interval;

i: variable for the aggregator constraints definition;

k: time interval;

K_C: participation coefficient adopted in the objective function definition;

$k^{SD}_{i-start}$: reference starting time of shiftable load specified by apex "SD" of user i;

$k^{SD}_{i-end_{max}}$: maximum end-time within user i wants the cycle of the shiftable load "SD" to be finished;

$k^{AC}_{i-start}$: air-conditioner cycle starting time as scheduled in reference profile for user i;

k_{i-end}^{AC}: air-conditioner cycle end time as scheduled in the reference profile for user i;

$lifecycles$: maximum number of cycles that the residential ESS can execute;

$lifeyears$: lifetime of the residential ESS;

M: high value constant, adopted for constraints definition;

P_{solar_n}: nominal power of the residential solar power plant;

P_{cycle}^{WM} :average power absorbed during a cycle by the washing-machine;

P_{ess_n}: nominal power of the storage system for a residential user;

t_{cycle}^{DW}: dish-washer cycle duration expressed as a continuous time variable;

P_{cycle}^{DW} :average power absorbed during a cycle by the dish-washer;

P_{cycle}^{AC}: average power absorbed during a cycle by the air-conditioner of a residential user;

$P_{max_{increase}}$: residential air-conditioner maximum power increase with respect to P_{cycle}^{AC};

$P_{max_{decrease}}$: residential air-conditioner maximum power decrease with respect to P_{cycle}^{AC};

P_{solar_n-c}: nominal power of the commercial solar power plant;

$P_{max_{increase}-c}^{AC}$: commercial air-conditioner maximum power increase with respect to its absorbed reference power at time t;

$P_{max_{decrease}-c}^{AC}$: commercial air-conditioner maximum power increase with respect to its absorbed reference power at time t;

P_{i-load}: load profile of residential user i, at common node;

P'_{i-load}: load profile of residential user i, at load terminals;

$P_{i-solar}$: actual produced power by i-user residential solar power plant, at common node;

$P'_{i-solar}$: actual produced power by i-user residential solar power plant, at PV plant terminals;

$P_{i-ess_{in}}$: injected power by i-user energy storage system, at common node;

$P'_{i-ess_{in}}$: injected power by i-user energy storage system, at battery terminals

$P_{i-ess_{ab}}$:absorbed power by i-user energy storage system, at common node;

$P'_{i-ess_{ab}}$:absorbed power by i-user energy storage system, at battery terminals

$P.U_{incomes_{summer}}$: per-unit summer incomes due to MB participation;

$P.U_{incomes_{winter}}$: per unit winter incomes due to MB participation;

RTE: Round trip efficiency of the ESS;

SoC_i: state of charge of user i;

$SoC_{decrease}$: state of charge decrease due to worsening;

SoC_{min}: minimum SoC of residential ESS;

SoC_{max}: maximum SoC of residential ESS;

$SoC_{initial}$: initial SoC of residential ESS;

$t^{DW}_{end_{max}}$: maximum time within the dish-washer cycle has to be completed, expressed as a continuous time variable;

t^{WM}_{cycle}: washing-machine cycle duration expressed as a continuous time variable;

$t^{WM}_{end_{max}}$: maximum time within the washing-machine cycle has to be completed, expressed as a continuous time variable;

t^{AC}_{cycle}: air-conditioner cycle duration, expressed as a continuous variable;

$P_{i-grid_{in}}$:injected power by the electrical grid of user i, at common node;

$P_{i-grid_{ab}}$:absorbed power by the electrical grid of user i, at common node;

$P_{grid_{max}}$: power limits of the residential electrical grids;

P_{load-c}: actual absorbed power by the commercial load, at common node;

P'_{load-c}: actual absorbed power by the commercial load, at load terminals;

$P_{solar-c}$: actual produced power by the commercial solar power plant, at common node;

$P'_{solar-c}$: actual produced power by the commercial solar power plant, at PV plant terminals;

$P_{grid_{in}-c}$: injected power by the electrical grid of the commercial unit, at common node;

$P_{grid_{ab}-c}$: absorbed power by the electrical grid of the commercial unit, at common node;

$P_{grid_{max}-c}$: power limits of the commercial electrical grid;

$P_{grid-injected}$: depending on the considered unit it equals $P_{i-grid_{in}}$ or $P_{grid_{in}-c}$;

$P_{grid-absorbed}$: depending on the considered unit it equals $P_{i-grid_{ab}}$ or $P_{grid_{ab}-c}$;

P^{SD}_{cycle}: average power absorption of the shiftable load specified by apex “SD”;

$p.f$: participation factor of users in a dispatching order execution;

$R_{incomes}$: residential units incomes due to MB participation;

$S_{incomes_{day}}$: summer incomes due to MB participation;

SD: it can equals WM or DW;

$T_{incomes}$: total incomes due to MB participation;

$U_{incomes}$: units incomes due to MB participation;

$W_{incomes_{day}}$: winter incomes due to MB participation;

With reference to the Figure 5.23 example only:

$\Delta^{ess}_{max_{in}}$: maximum power variation of the injected power of the ESS with respect to its reference profile;

$\Delta^{ess}_{max_{ab}}$: maximum power variation of the absorbed power of the ESS with respect to its reference profile;

P_n: nominal power of the battery adopted as example;

Introduction

Since the beginning of the world, human behaviour and technological progress have strongly affected each other. In every application field, the hardest challenge to be faced has been and continues to be promoting technological improvement adopting virtuous behaviours towards environment and human-health. Especially in the past, technical improvements occurred regardless of these principles, sometimes due to ignorance with respect to dangerous conducts and more frequently just for economic interests. In the last years, more and more care has been taken to face these problems. Focusing on the Italian electrical energy sector, latest years have been characterized by a continuously growing replacement of traditional generation with renewable one, in order to avoid pollution due to fossil fuels combustion. Moreover, it is important to highlight how many of these green power plants have been installed by domestic users, leading to a national electric system characterized by many distributed and low power generation plants that have never had visibility on the electricity market. In fact, the grid-code containing the regulatory framework for these markets has been developed in a period that did not present a high distributed renewable sources penetration. This new scenario combined with the unpredictability of renewable generation is responsible for the increasing difficulty in managing the national electrical system by the transmission system operator (TSO). The TSO is the central counterpart in the ancillary services markets, which are used to create power reserve and procure real-time resources. These are necessary in order to guarantee real-time balancing between generation and consumption that will never perfectly match the scheduled profiles of the energy markets. The traditional ancillary services market is mainly based on the dispatching of thermoelectric power plants, since they can be easily programmed and controlled. This is leading to a paradox: on one hand renewables are able to substitute pollutant traditional power plants, on the other renewables requires traditional power plants in order to operate the national system in a reliable and effective way. Over the last years this growing problem has been globally recognized and, concerning the Italian scenario, 2017 has been a turning point for facing it. In fact, ancillary services have become accessible to a larger variety of units enabling new alternative market participants other than the traditional ones. The purposes of this final dissertation is to consider how distributed energy resources can be exploited in the real-time balancing market, proposing a step-forward with respect to their actual applications in the Italian scenario.

The work can be better framed in the *virtual power plant* context [1], which has been implemented in Italy throughout Terna pilot projects, which have been promoted after the publication of decree 300/2017/R/eel [2]. In this work a virtual enabled mixed unit (UVAM, Unità Virtuale Abilitata Mista) has been considered as case study [3, 4]. Particularly, this analysis is representative of an aggregate constituted by 3000 residential units and a commercial one. In fact, it is worth noticing that in order to achieve a relevant power flexibility it is necessary to exploit many low power units. The coordination among all this units needs to be managed by a new market agent, namely the aggregator. The choice of considering an aggregate constituted by no-traditional energy plant has been taken in order to highlight the central role that final users could gain in the electricity market. The simulations performed in this thesis explore and evaluate the potentialities that these new players can introduce in the market through the aggregator coordination role. To properly coordinate all the units the aggregator must collect information on the available flexibility, thus every unit must communicate its availability to the aggregator that, evaluating the entire set of units, defines a cumulative flexibility level that the aggregate can provide. In this way, all the small units can achieve visibility in the balancing market increasing the amount of potential users, that, before decree 300/2017/R/eel, would have not been available to supply these kind of services. These new resources are generally identified as Distributed Energy Resources (DER), they can be generators, loads or storage systems. In this work it has been considered that each residential unit is enabled to install a solar power plant, an energy storage system, a controllable dish-washer, a controllable washing-machine and a controllable air-conditioner. On the other hand, for what concerns the commercial unit, it installs a controllable air-conditioning system. The mentioned flexibility is provided through load shifting of dish-washer and washing-machine, load modulation of the air-conditioner and smart management of the storage system. Only some residential units install these controllable devices and, in case, they are not obliged to provide their flexibility to the aggregator. To analyze the profitability of the aggregator it is necessary to gain information not only about the flexibility of the aggregate, but also on the remuneration that it may gain on the ancillary services market. This final dissertation focuses on the prices of the historical offers presented in the balancing market. In order to associate to each offer, submitted at a given price, a certain probability of being accepted in the market, a market-analysis tool has been developed using MATLAB software. Then, adopting the same software, two models have been implemented. The first one maximizes the incomes that can be achieved by the aggregator on the balancing market. Particularly, accordingly to the results obtained from the market analysis and to other specific problem constraints, it will define the bidding power quantity, the bidding time and the scheduling of the flexible devices. The second one, instead, focuses on minimizing the costs in order to accomplish a predefined dispatching order, pointing out the different flexibility contributes and capabilities of residential and commercial units. Following these lines, further developments can be achieved under different point of views. Firstly, focusing on the algorithm, the adopted approach is based on a centralized logic; implementing a distributed optimization algorithm would lead to lower computational times [5,6] [5,6]. Secondly, the adopted model can be extended including an higher amount of controllable devices, as thermal-heaters or CHP, moreover also technical limitations could be considered in terms of power gradients or network power flows. Finally, the adopted problem formulation can fit different economical models with different objective functions, therefore this allows to evaluate many remuneration logics.

The thesis is structured in five chapters, in the first one, a general overview on the Italian Electricity market structure is presented. Particular emphasis is given to the ancillary services market. In the second one, the recently changes occurred in the Italian national electricity system are presented, along with the introduction of Virtual Power Plant, Demand Response and Distributed Energy Resources concepts; a global overview on the active projects in the world is presented. Third chapter reports a detailed description of which are the Terna pilot projects enabled by decree 300/2017/R/eel along with the available results obtained by their initial running phases. Chapter four presents the economical analysis of 2017 balancing market data, obtained through a market-analysis tool developed through MATLAB software. Finally, chapter five presents the simulations obtained through the development of two optimization algorithms through MATLAB software. The first algorithm optimizes the achievable incomes by an aggregate that participates to the balancing market. Particularly, the optimal participation time, the power variation level and the schedule of flexible devices is computed. On the other hand, the second algorithm optimizes the available flexibility in order to face a predefined dispatching order, pointing out which are the contributes of both residential and commercial units.

Chapter 1

Italian Electricity Market

1.1 Historical dates

The Italian electricity market has been established by the legislative decree known as «Decreto Bersani» on March 1999; this was the answer to the European call for the constitution of an internal energy market (directive 96/92/CE, then abrogated by directive 2003/54/CE). To understand the reasons that have led to the constitution of the electricity market, the energy market scenario must be analyzed along the years. With this purpose, the electrical energy supply chain is reported, highlighting which have been the main changes affecting its different phases.

1. Before 1962 about 1270 electrical companies were operating on the energy supply chain without a rigorous organization (Figure 1.1), this impeded to reach useful coordination between different market operators;

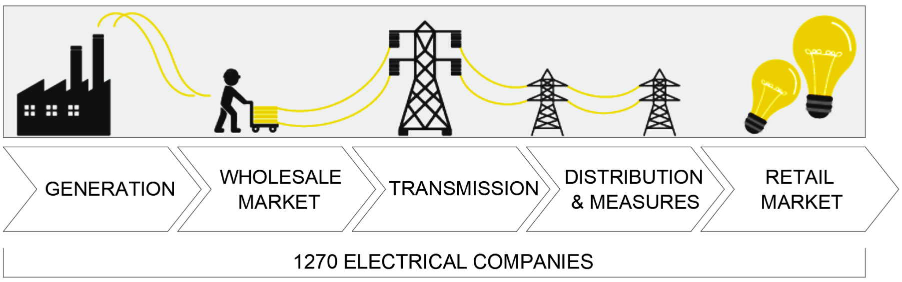

Figure 1.1: Supply chain - before 1962

2. On 1962 ENEL (Ente Nazionale Energia Elettrica) was founded to manage the entire supply chain as a state monopoly (Figure 1.2); the goal was to give a structured organization to the supply chain in order to increase its development;

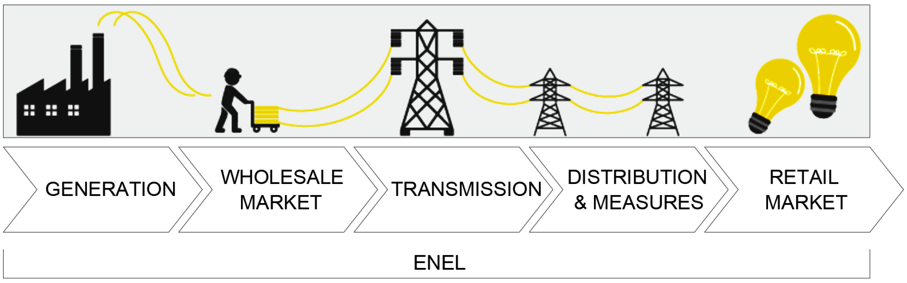

Figure 1.2: Supply chain - 1962

3. Between 1974 and 1986 ENEL invested on petroleum and nuclear energy but petroleum shocks (1974 and 1980) and Chernobyl disaster (1986) caused huge economical losses to the company; therefore, new monetary resources had to be found. This was one of the most relevant events that after a decade, in 1992, would have led to the privatization process of ENEL. In fact, ENEL was replaced by ENEL S.p.A., controlled by the Ministry of Treasury.

4. In the early '80s it was possible to observe a boost at the European level regarding the energy market liberalization process for the generation and sale sectors. The reasons that drove this process were related to a great technological improvement that made possible to efficiently produce energy also with small generation plants and not only with large ones, along with the energy demand increase. These two phenomena from an economical point of view led to a decrease of the socially optimal firm size and this was the reason for the liberalization and consequent creation of an energy market. Differently, with reference to the transmission and distribution sectors of the supply chain, the high coordination level required to efficently operate the activities precludes the possibility to introduce a liberalized structure;

5. In 1999 the European guidelines was implemented also in Italy with «Decreto Bersani» and the supply chain changed (Figure 1.3).

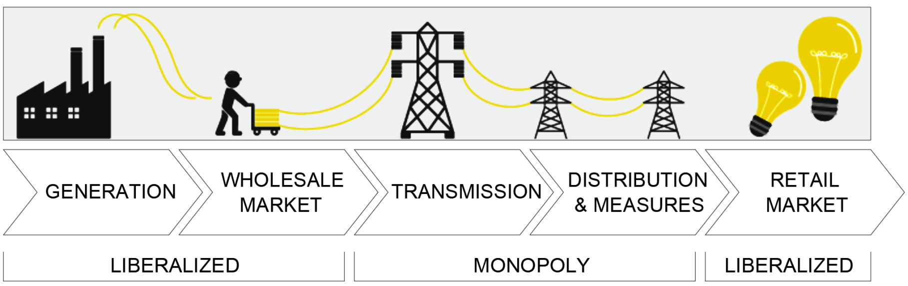

Figure 1.3: Supply chain - Actual

The transmission network is nowadays handled by TERNA S.p.A. while the Distribution network is handled by different companies as a local monopoly.

On the other hand, for generation and sales sectors the market is liberalized, with several companies involved.

1.2 Actual structure

The GME (Gestore Mercati Energetici) is the Italian company for the organization, focused on neutrality, transparency, objectivity and competition of the electrical market, natural gas market and environmental markets. It was set up by the GSE S.p.A (Gestore Servizi Energetici) that is a company wholly owned by Ministry of Economy and Finance. This ministry provides guidelines and provisions to ARERA (Autorità di Regolazione per Energia Reti e Ambiente) which has to actuate them. With reference to the electricity market organized by GME (named IPEX, Italian Power Exchange) producers and purchasers sell and buy wholesale electrical energy. It is important to highlight that this is not a mandatory market and electrical energy can be exchanged also by bilateral over-the-counter contracts (OTC[1]) that are registered on the PCE platform (Piattaforma Conti Energia) that is managed by GME and does not belong to the electrical market.The structure of the Italian power exchange market organized by GME can be outlined as reported in Figure 1.4. It is possible to distinguish between a Spot electricity market, a forward electricity market and the platform for the physical delivery of financial contracts concluded on IDEX (Italian Derivatives Energy Exchange).

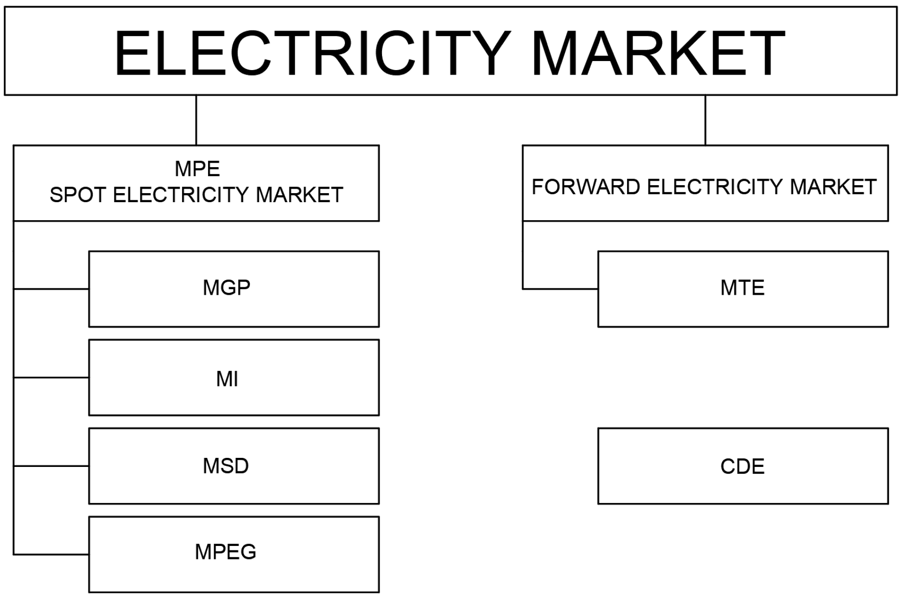

Figure 1.4: Electricity market structure

[1]OTC contracts are hendled outside the IPEX, the trade occurs directly between the producer and the buyer, specifying both energy quantity and energy price.

1.2.1 MPE - Spot electricity market

This market involves four different sub-markets that are the Day-Ahead market (MGP), the Infra-Day Market (MI), the Ancillary Services Market (MSD) and the Daily Products Market (MPEG).

1.2.1.1 MGP

MGP is an auction market where participants submit bids (asks) in which they specify the minimum (maximum) price at which they are willing to sell (purchase) energy. The MGP sitting opens at 8 a.m of the ninth day before the delivery day and closes the day before the delivery at 12 p.m; results are available within 12:55 p.m of the day before the delivery. It is important to point out that the acceptance of the bids/asks occurs just when the MGP sitting is closed, following an economic-merit order and taking into account transmission capacity limits between different geographic zones[2]. With reference to the accepted supply offers and demand bids of foreign virtual zones[3], they are valued at the equilibrium price of the zone to which they belong. Concerning the accepted demand bids of Italian geographic zones they are evaluated at PUN (National Single Price), which is the price that represents the average of the geographical zones equilibrium prices, weighted for the purchased quantities in each zone.

$$PUN = \frac{\sum_{k,i}(p_z^k \cdot Q_i^k)}{\sum\limits_{k,i} Q_i^k} \tag{1.1}$$

where:

$p_z = zonal\, equilibrium\, price;$

$Q_i^k = energy\, purchased\, in\, the\, area\, k\, by\, the\, player\, i;$

$k = k - zone;$

In Figure_ 1.5 a scheme relative to zonal subdivision of Italian transmission network is reported:

[2] A geographic zone is representative of a portion of the national transmission line that is divided in northern Italy (NORD), central-northern Italy (CNOR), central-southern Italy (CSUD), southern Italy (SUD), Sicilia (SICI), Sardegna (SARD).

[3] A foreign virtual zone is a point of interconnection with neighboring countries.

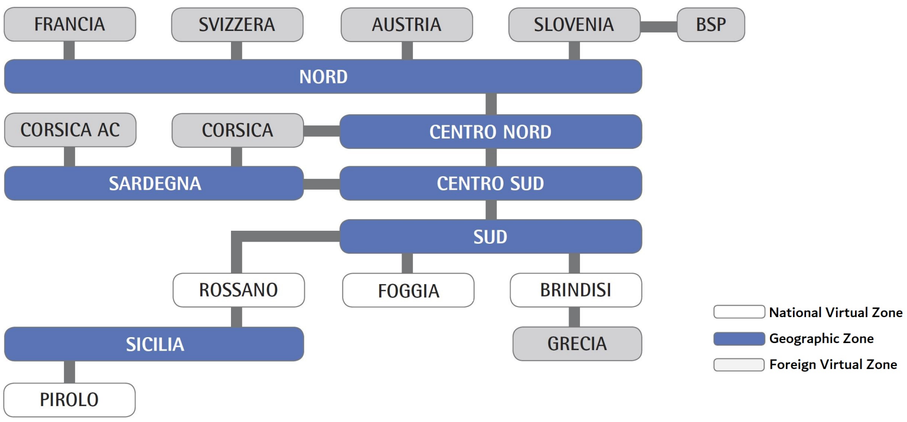

Figure 1.5: Italian transmission grid - zones

The acceptance process can be summarized in the following way, with GME acting as central counterpart:

- Supply offers are ordered by increasing price;
- Demand offers are ordered by decreasing price:
- The intersection between the two curves gives the equilibrium (clearing) price P_{eq} as shown in Figure 1.6, if no violation of transmission capacity of the lines occurs, this price is the sell/buy price and it is the same for the whole geographic areas. The accepted bids are the ones with a price lower than P_{eq} and the accepted asks are the ones with a price higher than P_{eq} ;

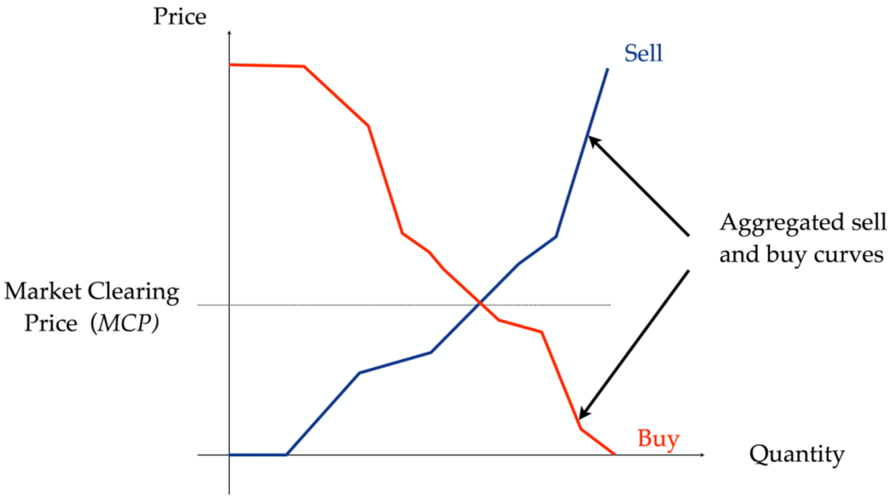

Figure 1.6: Equilibrium price evaluation

- If a violation of the transmission line capacity occurs, the market is splitted in two market zones[4]: import zone (downstream zone with respect to the violation) and export zone (upstream zone with respect to the violation);

- For both these market zones the same process just shown for the determination of the equilibrium price is repeated and two equilibrium zonal prices are found. If constraints are violated another zone-splitting occurs and the process continues iteratively until no capacity limit is violated.

The import zone clearing price results higher than the export zone clearing price, as in the import zone in order to satisfy the energy demand it is necessary to operate plants with higher production costs with respect to the ones operated in the export zone. The difference between the two zones clearing prices is given from the GME to TERNA as an incentive for the improvement of the transmission grid. For what concerns the OTC contracts they are also included in the evaluation of the MGP market by considering the offers as zero-price and the bids as no-price asks.

1.2.1.2 MI

MI market allows the participants to modify the scheduled power profiles defined in the MGP, which can be needed in order to allow the power plants to respect the technical limits after the MGP clearing or to update the previously submitted profiles according to better forecasts that are available close to the delivery time. Also in this case, as for the MGP, the power transfer limits are evaluated at zonal level. It takes place in seven sessions as reported in Table 1.2. In this case the demand bids are evaluated at zonal price instead of PUN. However, the offers selection criteria works analogously to the MGP. In order to avoid that consumers buy energy in the MGP and sell it in the MI at an higher price some rules are applied in the offer selection. On one side bids are valued at the higher price between the value obtained from the offers selection criteria and the PUN determined in the MGP. On the other, offers are valued at the lower price between the value obtained from the offers selection criteria and the PUN determined in the MGP. GME acts as central counterpart.

1.2.1.3 MSD

MSD market is operated by GME on behalf of TERNA. Its role is providing TERNA with resources for monitoring and managing the system relief of infra-zonal congestions, energy reserve and real-time balancing. Terna is the central counterpart and the accepted offers are remunerated at the price offered (pay-as-bid). The MSD is constituted by two phases that are MSD ex-ante and MB (Balancing Market). Both of them are developed in different sessions, 6 for the MSD ex-ante and 6 for the

[4] A market zone is an aggregation of geographic and/or virtual market zones; they are constituted if transmission line capacities are overcame during the evaluation of the equilibrium price.

MB). During the MSD ex-ante the scheduling phase for the system relief of infra-zonal congestions and energy reserve constitution occurs, the sitting for offer/bids submission is unique and occurs during MSD1 while the results are made known to the participants during the different sessions. MB instead is responsible for real time balancing, the first sessions of MB accounts for the submitted offers/bids during the first session of MSD ex-ante. In the MSD different services can be provided, namely:

- Resolution of the congestions occurring after MGP and MI clearing: if the clearing of MGP and MI markets reveals some congestions issues it is necessary to resolve them. For this purpose the enabled units (UA, Unità Abilitata)[5], controlled by UoDSs[6], must allow a variation in their power injection up to their lower and higher power limits. The variation that they can offer is computed with respect to the updated cumulative programs[7];
- Secondary power reserve: it is necessary in order to face the unbalances between generation and load at the national grid boarders and therefore restore the power exchanges and European frequency to their planned values. Every UA is requested to make available, with respect to the updated cumulative program, a symmetric secondary power reserve margin. These reserve is made supplied in two phases:
  1. Planning phase in which the reserve margin is made available with respect to the cumulative updated programs, or if it is necessary the cumulative updated programs are automatically modified in order to made available a secondary power reserve;
  2. Real Time Management in which for each UA this resource is used, based on an automatic system that sets power levels for each UA.
- Tertiary power reserve: according to activation time constraints we can define two typologies of tertiary power reserve: spinning power reserve and replacement power reserve. First one is used in order to restore the secondary reserve that could have been used; it is fundamental to restore it as soon as possible given its importance. The second one is used to restore the first one and to face load or non-programmable[8] generation variation or long interruptions of generation groups. A UP can be enabled to both increasing and decreasing

[5]A UA is a relevant production unit (UP, Unità di Produzione rilevante) which meets the requirements for the participation at least to one of the dispatching services, a UP is relevant if the total power of the generation plants under the unit is higher or equal to 10MW. For a deepening about production (UP) and consumption(UC, Unità di Consumo) units reffer to TERNA GRID CODE chapter 4.

[6]UoDS is the User of Dispatching and it is the grid user involved in the dispatching activity, this user menages one or more UA.

[7]The updated cumulate program of a UA is the power profile of a unit resulting after the MGP and MI clearing.

[8]such as renewable energy sources, on which we cannot have a perfect forecast.

tertiary reserve, or to just one service. The tertiary power reserve is created with respect to the updated cumulative programs.

- Balancing reserve: this is used to maintain a perfect balance between generation and consumption. In real-time operation the units that are exploited to carry out this task are the ones selected in the MSD ex-ante for the tertiary power reserve and the ones selected in MB. The balancing reserve power injection or withdrawal is referred to the binding power programs[9] .

It is worth to highlight that the above-mentioned services are not the only ones needed for the safety, reliable and good quality operation of the national electric system; in fact there are other services that cannot be exchanged in the MSD market and that are automatically provided as soon as a power plant is connected to the grid, which are briefly mentioned below:

- Primary frequency regulation;
- Primary voltage regulation;
- Secondary voltage regulation;
- Remote release;
- System re-establishment;
- Load rejection;
- Load interruption;

An electrical unit has to meet specific technical requirements in order to became UA, which are related to the power size and type of the unit since just the relevant-programmable units are eligible for being UA. Other requirements are specific for hydro power plants and they ask for the ratio between the energy that may be supplied in a day and the maximum power of the plant to be equal or exceed 4 hours, in this way the small hydro plants are automatically excluded. Moreover, depending on the technical characteristics of unit, it can serve different dispatching services. These technical features can be defined in terms of gradients. In fact, depending on the specific dispatching service, a maximum time $t_{max,1}$ can elapse after the variation request and its application and a minimum power variation (P_{min}) has to be guaranteed in a maximum time $t_{max,2}$, in Table 1.1 these constraints are reported and related to the specific dispatching service:

[9]Binding program is, for each enabled production unit, the electric energy to inject/withdraw after each sub-phase of the MSD ex-ante, defined hourly.

	t_max_1	P_min	t_max_2
Resolution of the congestions occuring after MGP and MI clearing	-	10 MW	15 min
Secondary power reserve	5 min	10 MW	15 min
Tertiary power reserve - first and second type	5 min	10 MW	15 min
Tertiary power reserve - spinning reserve	-	50 MW	1 min
Tertiary power reserve - replacement reserve	-	-	120 min
Balancing reserve	5 min	3 MW	15 min

Table 1.1: UA gradient constraints for dispatching services

Finally the service has to be kept for an unlimited time (replacement tertiary reserve) or for at least two hours (other services).

Offer contents and constraints Since the importance of the MSD market for the purposes of this thesis, it seems opportune to give a better overview about the offer structure of this market. Based on Grid Code Revision documents, available in their integrity on TERNA website [7], the main MSD changes concerning offers type and structure are reported.

Until 2009 MSD offers were structured as follows:

1. A unique increasing offer, up to UA maximum power level;

2. A unique decreasing offer, up to UA minimum power level;

3. A shut-down offer between UA minimum power and UA turn-off.

Recalling that in 2009 the Adjustment market was active in place of the Infra-Day market, the offer structure can be represented as in Figure 1.7 where increasing and decreasing offers are referred to the power level defined by the adjustment market clearing. It is worth to point out that offers are not differentiated over the available dispatching services. Obviously, operators formulate their offers with the goal of cover at least the marginal costs[10] and since the offer is unique it will be formulated in order to cover the marginal costs for the maximum available energy variation, this leads to high prices for MSD.

[10]Given the production cost $C_p = C_{cost\_fuel} \cdot (k_1 + k_2 E + k_3 E^2)$ of energy E, the marginal costs are defined as $C_m = \frac{dC_p}{dE} = C_{cost\_fuel} \cdot (k_2 + k_3 E)$ and are the additional costs required for the production of 1MWh more.

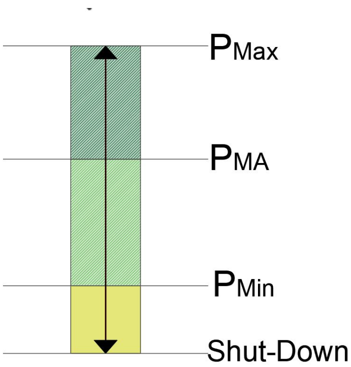

Figure 1.7: MSD offer structure until 2009

In 2010 a different offer structure was introduced, the main differences with respect to previous one are:

1. Increasing or decreasing secondary reserve offer;
2. Multiple offer structure for other services, up to 3 steps for MSD ex-ante and up to 4 steps for MB;
3. Minimum shut-down offer, minimum start-up offer , respectively refers to bringing the power to its technical minimum or to turn-on a previously turned off plant setting its power to its technical limit;

In 2011 slight modifications occur, without changing the offer structure:

1. A Start-Up offer can be supplied both for MSD ex-ante and MB, this offer is presented in € and not in €/MWh as the minimum start-up offer; it has to be lower than the Start-Up CAP[11].
2. Dispatching market is opened to non-turbogas thermoelectric units;
3. During MB sittings it is possible to participate just with offers that are better with respect to the previous MSD ex-ante sitting as explained in the following;
4. MB offers are referred to the previous MSD ex-ante sitting and no longer to the Infra-Day market;

In 2013 the following integration took part:

1. Set-Up modification offer[12] introduction for thermoelectric units, with reference both to MSD ex-ante and MB; it has to be lower than the Set-Up modification CAP;

[11] CAP means Capped Rate and refers to a maximum value that can be assumed, it has the same meaning when used for Start-Up, Shut-Down or Set-up modification

[12] Set-Up modification refers to the change on the active thermoelectric groups in a combined-cycle thermoelectric plant.

In Figure 1.8 graphical representation of the actual MSD market is reported. MI has been introduced in place of MA and it is taken as reference for the MSD ex-ante scheduling; relatively to MB the previous MSD ex-ante session is taken as reference. At each step a couple (Price [€/MWh]; Quantity [MWh]) is associated, these offers are ordered by increasing price.

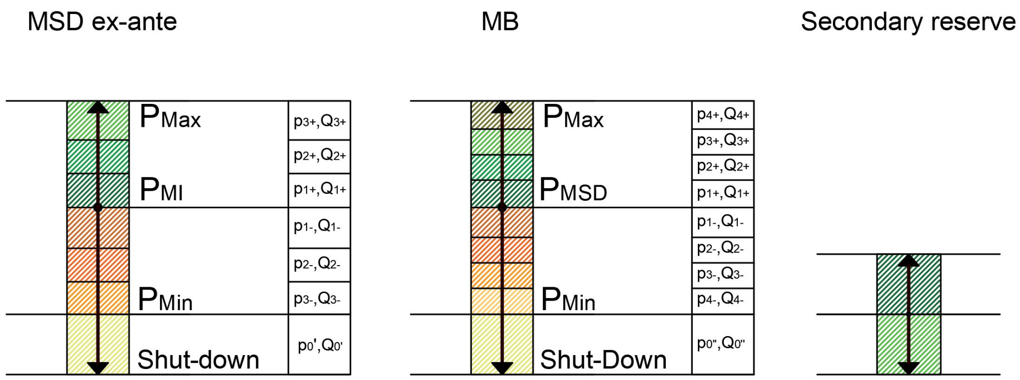

Figure 1.8: Actual MSD offer structure

As stated before, some constraints must be respected with reference to the presented offers. Particularly, UoDSs offers must consist of non-negative (Price;Quantity) couples, excepted for Shut-Down offer, and the convexity principle must be respected, as reported in Figure 1.9

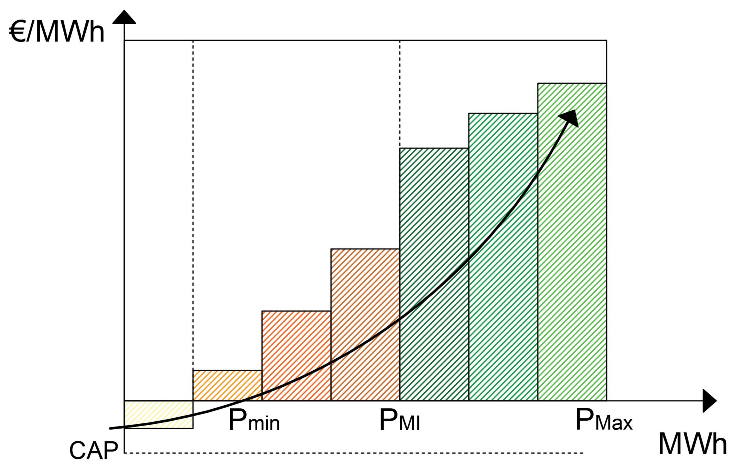

Figure 1.9: Convexity Principle

If the UdD does not respect this constraint the offers are automatically modified in order to match them. Particularly, for MSD ex-ante it has to be verified that:

- Minimum Start-up offer has to be lower than the minimum selling price, otherwise it is modified and set equal to «Other Services» minimum selling price as reported in Figure 1.10

- The maximum buying price has to be lower than the lowest selling price, otherwise it is modified and set equal to the lowest selling price, separately for «Secondary Reserve» and «Other Services» as reported in Figure 1.11 ;

- The Shut-Down offer has to be lower than the lowest buying price, otherwise is is modified and set equal to the «Other Services» minimum buying price as shown in Figure 1.12;

- The Shut-Down offer has not to be lower than the Shut-Down CAP, otherwise it is modified and set equal to the Shut-Down CAP;

- The Start-Up offer has to be lower than the Start-Up CAP, otherwise it is modified and set equal to the Start-Up CAP;

- Set-Up modification offer has not to be higher than the Set-Up modification CAP, otherwise it is modified and set equal to the Set-Up CAP.

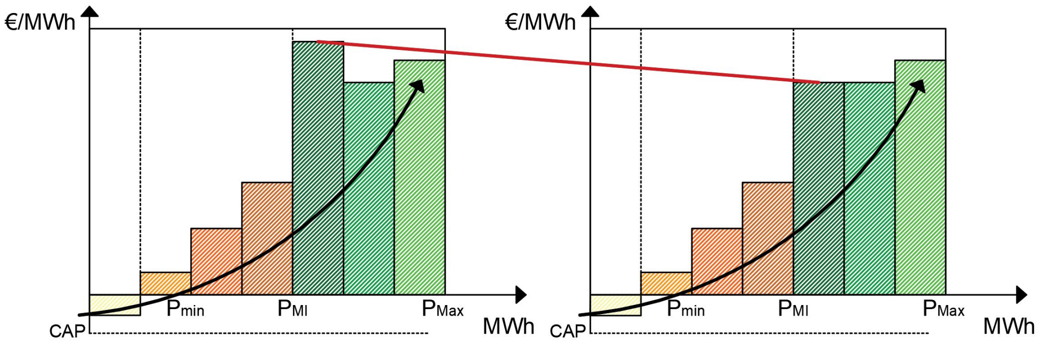

Figure 1.10: MSD constraints matching

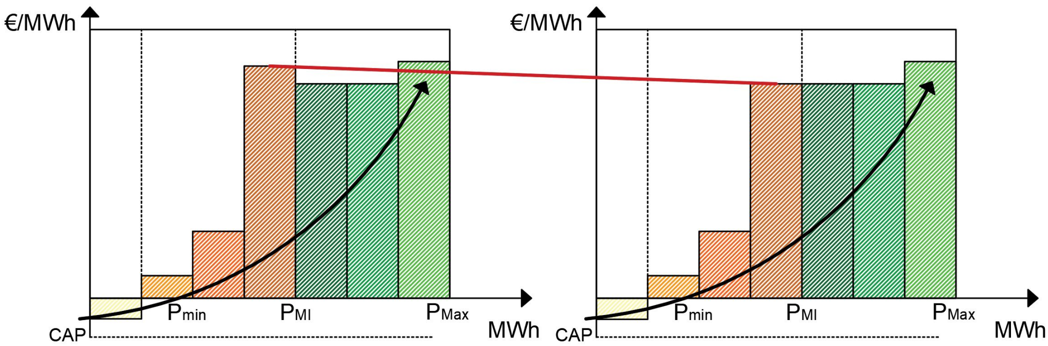

Figure 1.11: MSD constraints matching

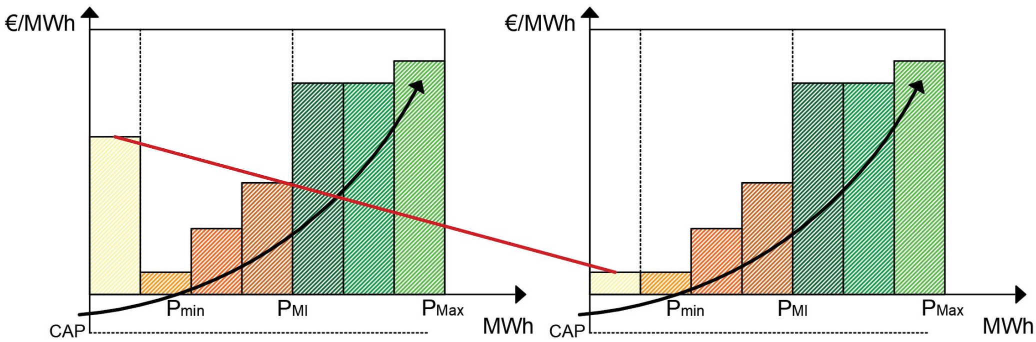

Figure 1.12: MSD constraints matching

MB market also has to respect these constraints; moreover, an offer is valid just if it has been improved with respect to MSD ex-ante, this means that, for MB market:

- Start-up offer has not to be higher than the Start-Up price offered in MSD ex-ante;
- Minimum Start-Up offer has not to be higher than the minimum Start-Up price offered in MSD ex-ante;
- Minimum Shut-Down offer has not to be lower than the Minimum Shut-Down price offered in MSD ex-ante, with reference to «Other Services».
- Set-Up modification offer has not to be higher than the Set-Up modification price offered in MSD ex-ante;

Additionally to offer prices constraints, UoDSs have other obligations. Particularly, relative to their enabled services, they have to offer:

- One price for the selling offers and one price for the buying offers, respectively for increasing or decreasing secondary reserve energy injection;
- Between one and three *Price-Quantity* pairs for selling and buying offers relative to Other Services in MSD ex-ante. These offers have to be formulated in accordance to power limits introduced by both the reference programme[13] and the power constraints of the considered plant.
- Between one and four *Price-Quantity* pairs for selling and buying offers relative to Other Services in MB. These offers have to be formulated in accordance to power limits introduced by both the reference programme and the power constraints of the considered plant.

[13]Reference program is the program used as reference in MSD programming phase for Other Services offers, it has been introduced to be able to clear MI2 while MSD1 is closing is sitting. If this program is not supplied by UoDSs the updated cumulative program of the first energy market session that precedes the first sub-phase of the programming session is used instead of it.

- One price for Minimum offer;
- One price for Shut-Down offer;
- One price for Start-Up offer;
- One price for Set-Up modification offer;

Essential Units Previous mentioned constraints refers to all UA however, some of them play a fundamental role for the national electric system security, for this reason the offers presented by them are almost always accepted. In order to avoid that UoDSs owning these units act opportunistic behaviors, rising a lot the price of their offers with the security of their acceptance, grid code regulates with particular constraints their participation in the ancillary services market. Particularly, both selling and buying offers have to be formulated at the variable costs associated to the UAs supplying the service.

1. Essential units have to submit their offers during the programming phase, along with the specific units to be activated in order to cover the essential [14] capacity for secondary power reserve;
2. Essential units have to respect offer constraints if the difference between the UoDSs essential replacement reserve in the programming phase and the sum of the latest available cumulative updated programs of the UAs on UoDSs titolarity is positive. This is applied to thermoelectric units, for the mentioned difference;
3. Essential units have to submit their offers during the programming phase, along with the specific units to be activated in order to cover the essential tertiary rotating reserve;
4. Relatively to MB, the submitted offer quantities has not to be lower than the once offered during programming phase, net of accepted quantities.

TERNA will verify if the offer prices are correctly formulated at the UA variable costs.

Amounts accepted and remuneration

[14] Essential capacity of a UoDSs, with reference to secondary o tertiary reserve, is computed as the difference between the needed reserve in a zone, identified by the specific configuration in which the national grid is considered, and the secondary reserve available from other UoDSs.

MSD ex-ante As already explained, planning phase consists of different sub-phases, that will end progressively one after the other, in the meanwhile more than one sub-phase could be open at the same time therefore, as shown in Table 1.2. In this paragraph the terms «preliminary» and «advance» are used as reference for hourly periods that belong to more than a sub-phase, if this term is absent it means that the sentence is referred to hourly periods that belong to just one sub-phase. With reference to each sub-phase, operator defines the hourly final cumulative program[15] and the hourly reserved[16] quantities for the Secondary Reserve and Other Services; it also defines the hourly preliminary final cumulative program and the hourly quantities reserved in advance for the Secondary Reserve and Other Services. The accepted offers are valued at the accepted price, since it is a pay-as-bid market. GME sends these information to each UoDSs along with final cumulative programs and MSD preliminary cumulative programs. TERNA sends to each UoD the procured secondary reserve half-band and the secondary reserve half-band preliminary procured that are quantities exclusively reserved for Secondary Reserve. TERNA communicates to each UoD also the binding program and the preliminary binding program. Every change in the technical information, dispatching service unavailability or any constraint on daily energy amounts for hydroelectric plants or pumping units must be communicated by UoD to the operator as soon as possible, in case of technical variations they are recorder in the RUP (Registro Unità di Produzione)[17]. These units will receive dispatching orders accordingly to their new status.

MB TERNA defines the valid quantities for each MB sub-phase evaluating the offers presented by UoDs for MB purposes and the adjusted quantities of programming phase that instead are used for balancing purposes. For each sub-phase the accepted and reserved quantities are communicated to each UoD before the closing of the next sub-phase. If a balancing action is required at a given minute, grid operator selects the cheapest offer however, for the sake of system security, the economic merit order can be overcomed. Dispatchment orders contain the indication for modified binding program[18] definition. TERNA can revoke dispatching orders before their execution. Regarding each relevant period and each dispatching service, TERNA defines the accepted quantities and their remuneration pay-as-bid[19]. For what con-

[15]Final cumulative program is the program obtained by the sum of the updated cumulative program and the accepted quantities on MSD ex-ante;

[16]With the term reserved we identify quantities that could be accepted in the next sub-phases.

[17]Enabled Unit Register, kept by the Operator, managed in Gaudì (software), contains the data, technical parameters and authorisation for participation in the various markets, for each significant production unit, non-significant production unit, and virtual import and export units.

[18]Modified binding programme refers to the binding power programme (average power corresponding to binding programme for each hour and UA) as modified by dispatching orders sent to the unit, and referring to the centre band of the level of the frequency/power regulation.

[19]It is worth to point out that up to 2016 remuneration could have been different from pay-as-bid because of the presence of «REVOCA» and «NETTING» offer types.

cerns Start-Up and Set-Up modification offers their are valued after MB clearing and the start-up or set-up number is computed considering their actual number during MB and their number as planned in updated cumulative programme that has to be subtracted, this difference is multiplied by the relative offered price.

In Table 1.2, the timeline regulating the different market session is reported.

Reference Day	D-1				D															
	MGP	MI1	MI2	MSD1	MB1	MI3	MSD2	MB2	MI4	MSD3	MB3	MI5	MSD4	MB4	MI6	MSD5	MB5	MI7	MSD6	MB6
Preliminary information	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
Operating of sitting	8.00**	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*
Closing of sitting	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
Provisional results	12.43	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Final results	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	#

* time refers to the day D-9
** time refers to the day D-1
°bid/offers entered in MSD1 are used
#dispatching rules

Table 1.2: Timeline of activities on the MPE referred to day D

1.2.1.4 MPEG

MPEG market allows the trading of daily products with the obligation of energy delivery. All participants of the electricity market and of PCE are admitted in this market and they can operate in a continuous trading mode, GME acts as a general counterpart. The daily products that can be negotiated are:

- Unit price differential, in which the price traded for the daily product is referred to the PUN;
- Full unit price, in which the price is referred to the daily product without any reference to other prices;

For both these typologies, two different delivery profiles can be negotiated:

- Base load, listed for all calendar days and all day long (0 - 24), whose underlying is the electricity to be delivered in all the applicable periods belonging to the day being traded;
- Peak Load, listed for the days from Monday to Friday (8 - 20), whose underlying is the electricity to be delivered in the applicable periods from the ninth to the twentieth day belonging to the date subject of trading.

MPEG market has been required by many operators in order to negotiate spot products with a payment horizon of M+2. The sessions of the MPEG take place on weekdays, as specified in the GME website and here reported:

- from 8.00 to 17.00 of D-2. If D-2 is a public holiday, the session will take place from 8.00 to 5.00 p.m. on the working day immediately before;

- from 8.00 to 9.00 of D-1, only if such day is not a public holiday, It follows that if the day D is preceded by a public holiday, the trading session for the product to be delivered in D will take place only from 8.00 to 5.00 p.m. on the first working day prior to the day D*.

* On Friday they will be traded:

- From 8 to 9 the products to be delivered on Saturday;

- From 8 to 17 the products to be delivered on Sundays and the products to be delivered on Monday and Tuesday (the latter product will also be traded from 8.00 to 9.00 of the session which takes place on Mondays).

1.2.2 Forward electricity market

1.2.2.1 MTE

MTE market is the venue where long term contracts with delivery and withdrawal obligation can be traded; the time horizons of these contracts are monthly, quarterly and yearly. GME acts as central counterpart and the negotiation is continuous over time. Contracts that are negotiable in this market are Base-Load and Peak-Load; the monthly basis contracts are registered on the PCE and the same can be done also for OTC bilateral contracts. The sessions will take place from Monday to Friday, from 09:00 to 17:30, except on the next-to-the-last day of open market of each month, when the closing time is advanced to 14:00 for operational reasons. Moreover the sessions of the MTE won't be held on: all Saturdays, all Sundays, 1st January, Friday before Easter, Monday after Easter, 1st May, 15th August, 24th December, 25th December, 26th December and 31st December.

1.2.2.2 CDE

CDE is the venue for registering transactions which correspond to financial electricity derivatives contracts concluded on IDEX and for which the participant has requested to exercise the option of physical delivery in the electrical market.

1.3 Electricity market trend

In the following the electricity market trend of the last 10 years is summarized based on the historical data available on TERNA, GME and ARERA websites.

1.3.1 Day-Ahed and Infra-Day market

Figure 1.13 shows the Italian energy production trend since 2007. About hydro-electric production the produced energy is strictly related to the rainfall level, the eligible geographic sites for hydro plants installation have already been exploited, therefore the amount of installed plants will not change a lot in the future. According to this, in 2017 it is possible to impute the lowest hydroelectric production over last 10 years to the lowest rainfall level over last 5 years in the north of Italy where the most of these plants are installed. Concerning the thermoelectric production in 2017 it rises to the highest levels since 2012, this has been driven mainly by two factors: low hydroelectric production and French nuclear crises[20] . With reference to renewable energy production, over the years a continuous increase of Renewable Energy Sources (RES) penetration is observed, this increase is also responsible, net of hydroelectric production, of a slight decrease of thermoelectric production.

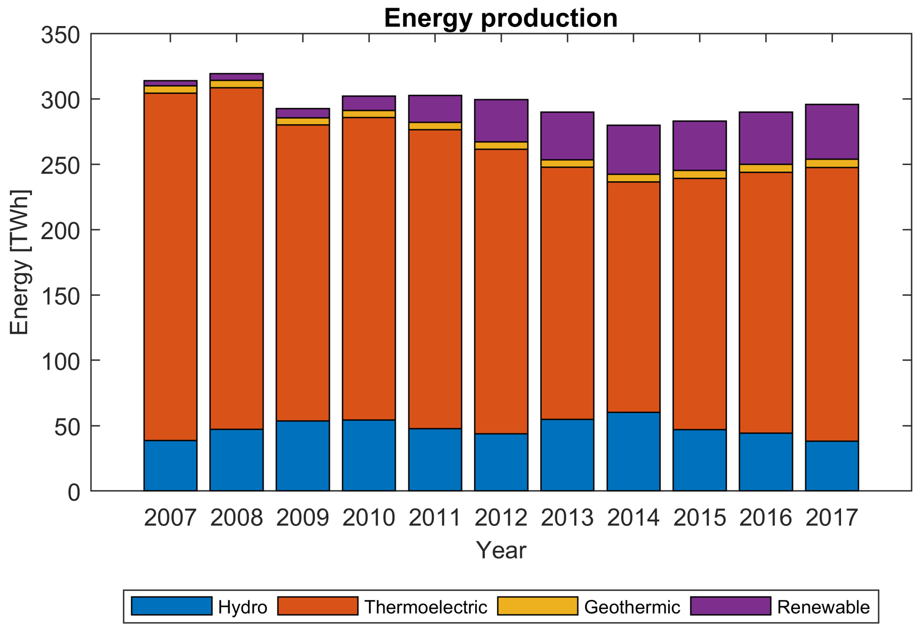

Figure 1.13: Italian energy production over last 10 years

Obviously, the generation mix has a direct reflection on the market prices. Focusing on PUN variation from 2016 to 2017 it is possible to relate its increase to the higher price of natural gas (PSV), required for thermal power plants operation, and to the higher costs of internal production with respect to French energy importation. The relation between PUN and PSV is reported in Figure 1.14.

[20]Italy and French exchange electrical energy through the electrical market, particularly Italy imports nuclear French. In 2017 many French nuclear plants were out of order due to extraordinary maintenance, for this reason Italian thermoelectric plants had to cover this energy lack.

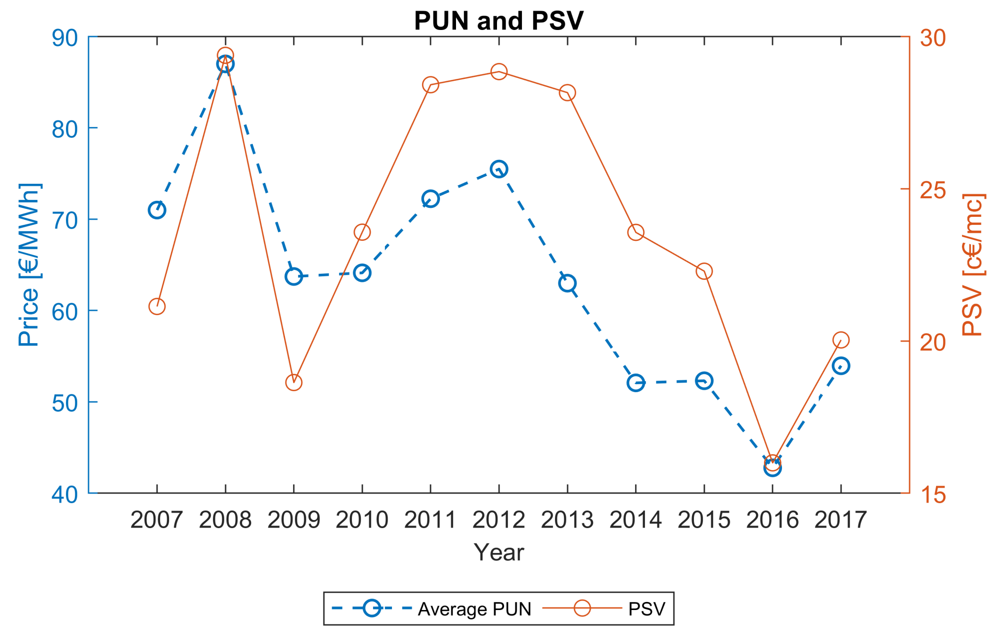

Figure 1.14: PUN and PSV trend over last 10 years

Concerning the MGP market the energy exchange reaches the higher value of the last 5 years with 292 TWh (211 TWh exchanged on the IPEX, 81 TWh with OTC). This volume corresponds to the accepted quantities reported in Figure 1.15.

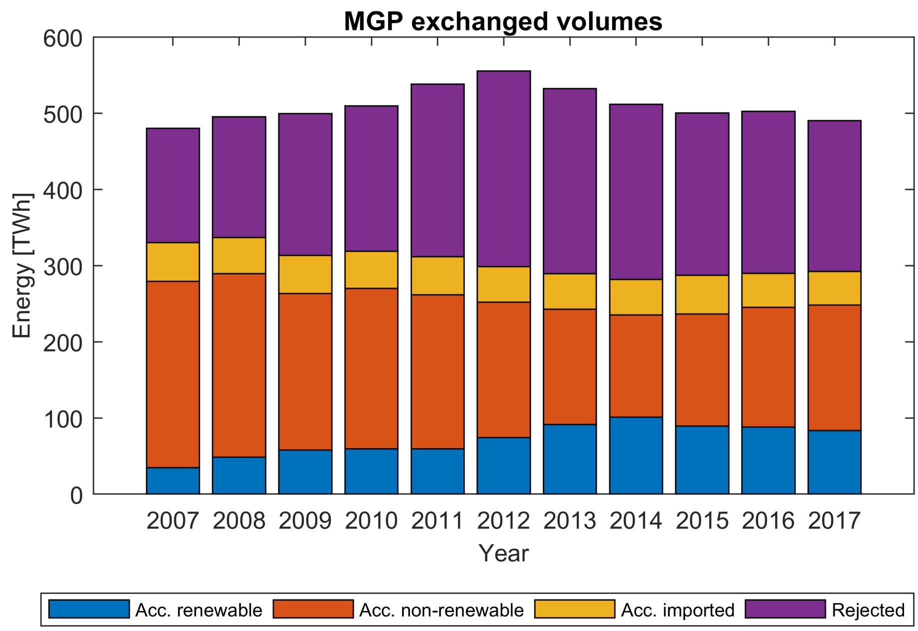

Figure 1.15: MGP offers over last 10 years

In Figure 1.16 the MI trend over last 10 years is reported. Many changes affected the structure of this market starting from 31/10/2009 in which MI was created in place of the older adjustment market (MA). In 2011 the number of sessions increases to 4, in 2015 it reaches 5 and nowadays it counts 7. It is possible to observe how the volumes traded on MI follows a continuous increase thanks to the increased number of sessions that allows a trading closer to real time, actually in 2017 the traded volumes are lower than the historical maximum registered in 2016 due to a reduction that mainly interests the MI1 and MI2.

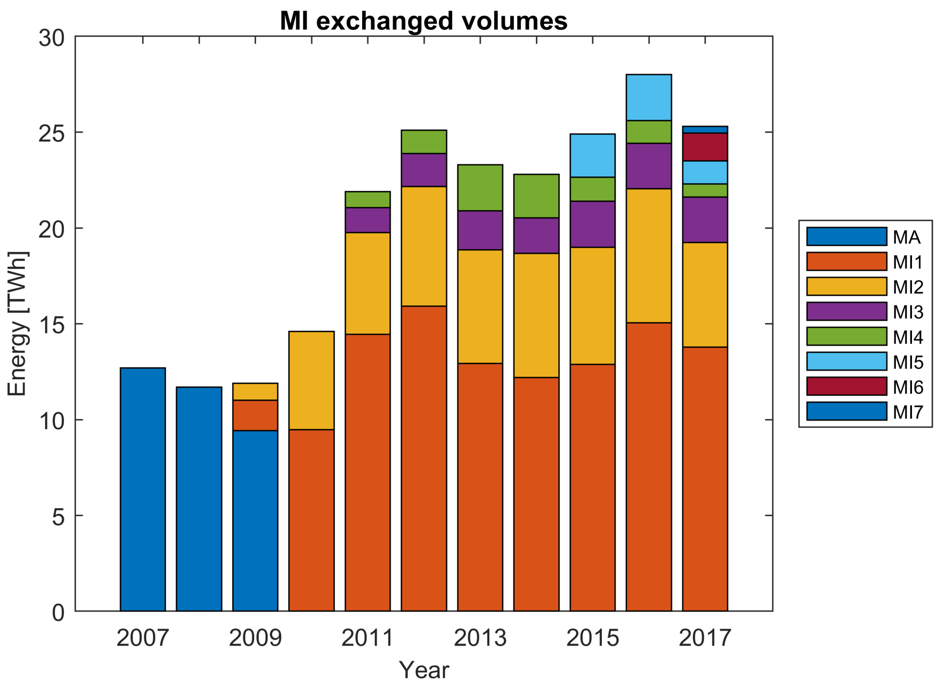

Figure 1.16: MI offers over last 10 years

Looking at Figure 1.17 the MI prices trend is reported, over the years it has reduced following the same trend of PUN, maintaining a slightly higher value. With respect to 2016, 2017 MI prices increases. The main volumes on MI are exchanged by thermoelectric power plants while renewable energy sources decrease their participation. Among RES the higher contribute is given by wind power plants that decrease their injection program after MGP clearing.

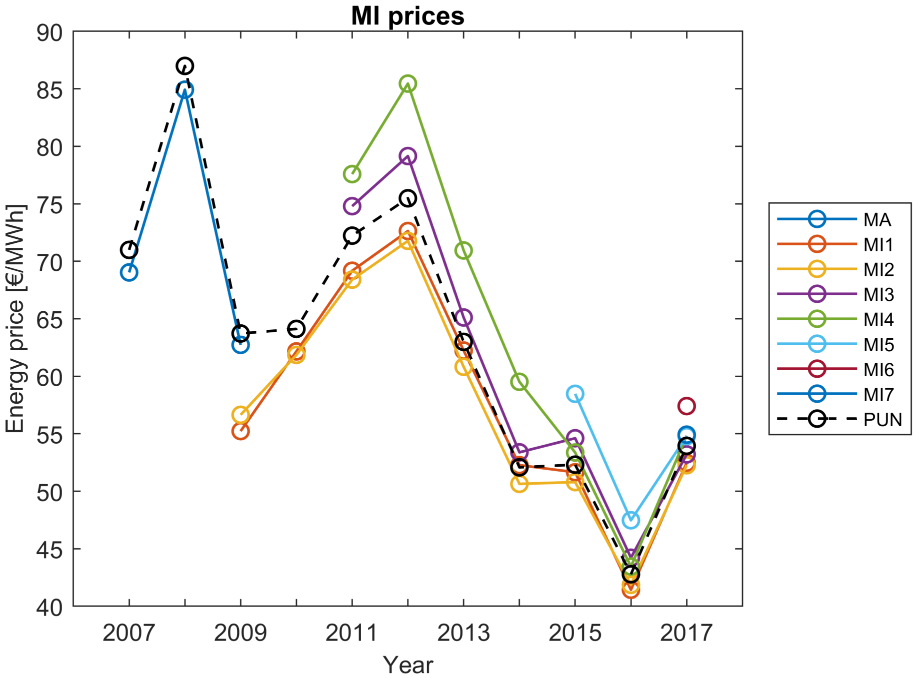

Figure 1.17: MI prices

1.3.1.1 Renewable generation effect on MGP market

As observable in Figure 1.13 last years have been subjected to a constant increase of RES plants. As known, this kind of generation is characterized by an high uncertainty level, this is due to the difficulty in forecasting the primary energy source required by these plants; focusing on wind and solar power plants, over the years many methods and techniques have been developed to increase the quality and the precision of weather forecasts. Focusing on the residual demand, evaluated as the total demand of consuming units, net of the demand covered by RES and not relevant production units, a deep change can be observed over the years. It can be verified that the residual load is decreased during central hours of the day, this because the solar production reaches its maximum level in that period. On the other end, in the evening the curve gradient increases, according to the fact that solar production decreases and demand profile increases. This leads to a difficult management of the thermoelectric units, in fact they cannot be competitive in the market when RES production is high and due to technical limits they cannot be started-up and shutted-down repeatedly, the final result is that in many hours these thermoelectric units have to offer a price that is to low for fixed costs covering and can only compensate the marginal costs of the unit. Moreover, high gradients would require power plants to quickly rise-up their production, which is not always possible due to technical issues. These phenomena have a direct reflection on MGP prices that will result in:

- Increase of average prices when no RES production is available or its contribute is low;
- Decrease of average prices when RES give high contribute to energy production;
- Highest prices are observed during the evening.

These aspects can be appreciated in Figure 1.18 where the prices of the years in which the RES experienced their higher expansion in national electric system are reported. It can be easily recognized how gradients in the middle hours of the day increased and how this is related to PUN variation as explained above.

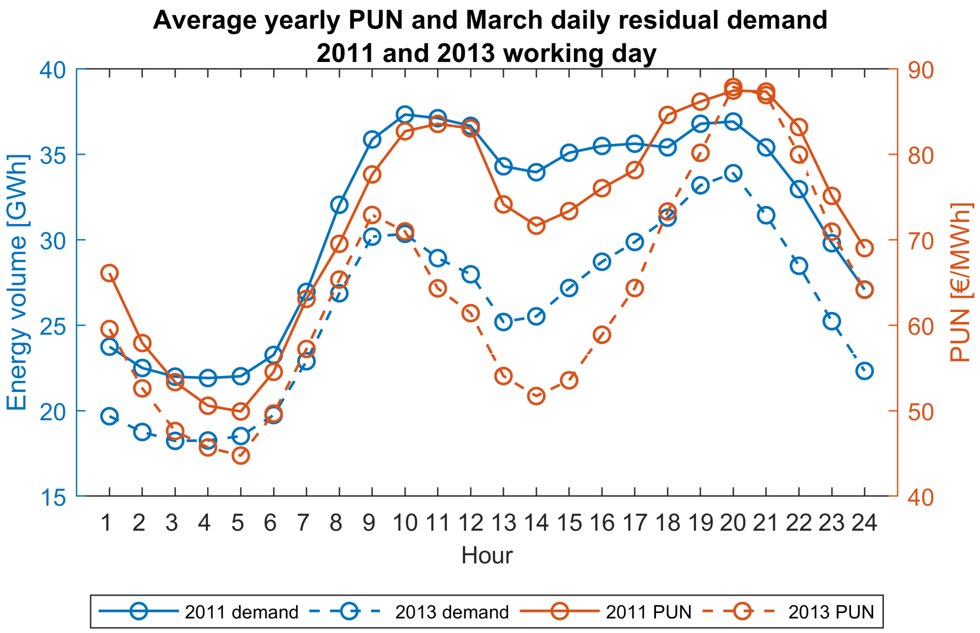

Figure 1.18: Average yearly PUN and March daily residual demand
working day - 2011 and 2013

For the sake of completeness it can be observed that from 2011 to 2013 the residual demand decreases, this phenomena can be related to the economical crises that affected Italy and to efficiency improvements.

1.3.2 Ancillary Services Market

In Figure 1.19 and 1.20 the exchanged volumes in the MSD market over the last 7 years are reported. It is possible to distinguish between increasing and decreasing offers that are respectively identified by «OFF» and «BID»; this nomenclature is the same as the one used by GME on his website. An «OFF» offer means that a UA is offering to TERNA an increase of its injected power into the grid, therefore if TERNA accepts this offer it has to pay-as-bid the UA , oppositely a «BID» offer means that a UA is offering a reduction of the injected power and if this offer is accepted UA has to pay-as-bid TERNA.

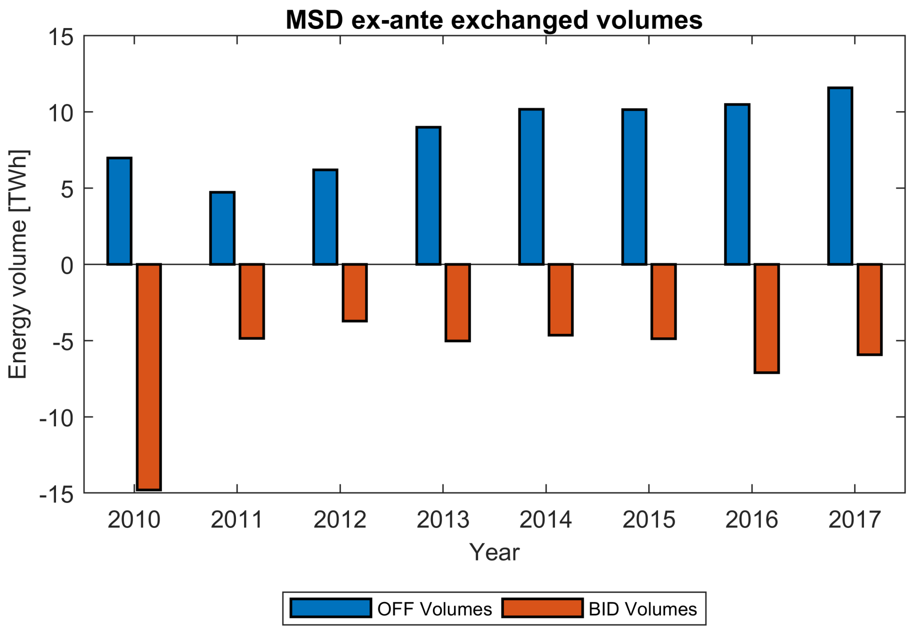

Figure 1.19: MSD ex-ante exchanged volumes

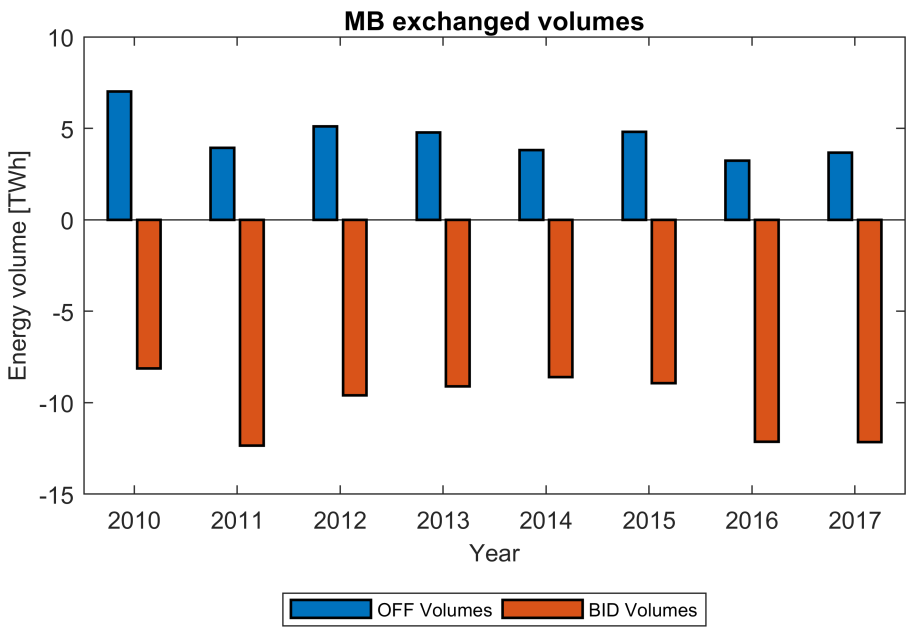

Figure 1.20: MB exchanged volumes

In Figure 1.19 it can be observed that over the years the volumes exchanged in programming phase have almost constantly increased, this phenomenon is strongly related to the penetration of renewable energy sources which effect can be, in first analysis, observed in the increase of «OFF» quantities. Instead, in Figure 1.20, it can be observed that the volumes sold by the operator in MB are higher than the bought ones, this because part of the energy bought during programming phase is sold during MB. A last remark can be done analyzing the ratio between the amount of energy exchanged during energy market and the amount of energy exchanged during ancillary services market, which trend is reported in Figure 1.21

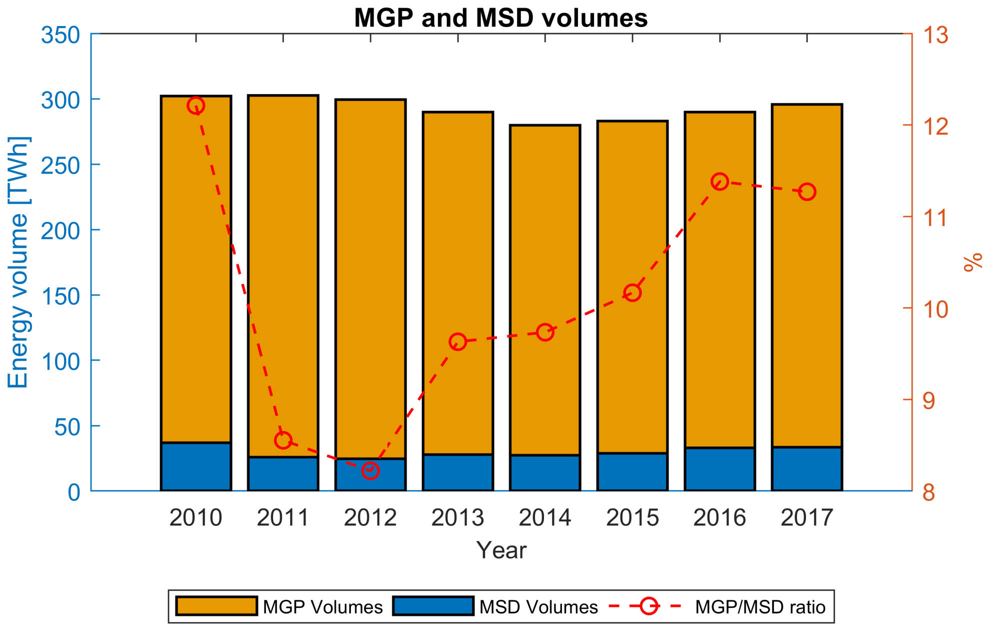

Figure 1.21: MGP and MB volumes comparison

The ratio between MGP and MSD can be read as as an indicator that shows how much the market is moving through a real-time management instead of a programmed management. Apart from 2010, focusing on the trend from 2011 up to 2017 it is possible to observe that the MSD quantities that are exchanged are being more and more consistent with respect to the quantities exchanged in MGP, this suggest that electrical market tends to move through a real-time market.

1.3.2.1 Renewable generation effect in MSD market

As for MGP, also MSD market trend can be analyzed pointing out its strictly relation with RES integration in the national electric system. In the previous paragraph it has been reported how the RES penetration have changed the residual demand profile over years, particularly it is important to distinguish between a residual demand

and an effective residual demand: residual demand is the total demand of consuming units net of the demand covered by RES and not relevant production units; the effective residual demand differs from the previous one because of the uncertainty related to RES production and load consumption forecasts. In order to face this uncertainty, higher reserve margins have to be constituted in MSD. However, since after MGP clearing many thermoelectric plants (that practically are the only ones used for regulation services) result shutted-off in favor of RES plants that are fully exploited, it is necessary to programme the start-up of these thermoelectric plants during MSD in order to guarantee the necessary reserve margin; these aspects make the reserve constitution in MSD more expensive and technically difficult. Regarding this aspect, when the residual electrical demand is low (high RES production) many thermoelectric plants work close to their minimum power level and, in order to guarantee enough decreasing reserve, pumping plants can be turned on so to increase the load, that for injection and withdrawn balance purposes is equivalent to reduce the injected power of thermoelectric plants. However, sometimes this could not be enough and grid operator could be forced to curtail renewable energy production or the quantity of imported energy in order to satisfy the decreasing reserve safety requirements.

Chapter 2

New Dispatching Resources

In chapter 1 the effect of renewable energy sources on the ancillary services market has been pointed out; it highlights the ineffectiveness of traditional power plants to answer the increasing ancillary services demand. Therefore, in order to decrease MSD market expenditures, it is fundamental a profound revision of the enabled actors in this market. The most natural approach to achieve an enlargement of the active players in the market is reducing the minimum technical requirements for the MSD participation. In other words, this means lowering down both the minimum power level and the duration of the requested services in order to enable smaller power plants to participate to the real time market. Another solution to increase the offers on the MSD could be allowing the participation also to non-programmable units, for example to a RES coupled with an energy storage system. Finally, a very precious and exploitable resource could be the *Demand Response* ("DR"). Basically, the DR is based on the idea of adapting the load to the available generation instead of altering the produced power to meet the demand. With respect to the interruptible load service, which is limited to large consumption units, the concept of DR can be widespread also to small loads.

2.1 Demand Response

Up to some years ago only two different players were involved in the national electric market: on one side the producers, on the other the consumers. This net distinction changed during the last decade since small generation units have been installed at distribution level and final users are nowadays also injecting power into the grid. The role of the final user is therefore switching from a passive to an active one. This new type of final user has been called prosumer to remark the fact that it can both consume and produce electrical energy. The mixed role of the *prosumer* let him respond in different ways to the electrical system behavior injecting or withdrawing energy according to a grid-user customized logic that can be improved and optimized exploiting the DR. A first example of DR can be given looking at the different electricity prices throughout the day of the final users, in fact during night and morning hours the electricity cost is lower than the one observed during the day; users that have in their contracts a multi-hour electricity energy price will try to shift their consumption in the cheapest hours. Another example can be given analyzing a PV farm hybridized with a storage system, in this case the best strategies of buying/selling can be achieved exploiting the buffer of the storage system. However, even if the just mentioned behaviors are classifiable as DR ones, nowadays DR can be exploited more thoroughly. This aspect will be pointed out in the next section where the concept of the Virtual Power Plant (VPP) will be introduced.

2.2 Virtual Power Plants

In literature [1] there is not a unique definition for a Virtual Power Plant, in this thesis it will be defined as a multi-technology, multi-site and multi-objective aggregate of distributed energy resources[1]. Moving through the just given definition it is possible to highlight the advantages of the VPP. First of all, they can aggregate different kinds of technologies as RES, energy storage systems, generation/cogeneration units and controllable loads. Secondly, these units may not be localized in the same area, but they can be displaced all over the entire transmission and distribution network. They will act under the control of an aggregator. Thus, a VPP can be exploited to achieve different technical and economical goals. For instance, it can be used to manage optimally all the DER inside the VPP supplying ancillary services to the main network. Therefore, a VPP can participate to transmission and distribution system stabilization as well as taking part to electricity market, through a VPP aggregation each DER reaches visibility up to the transmission level. A common subdivision when speaking about VPP is the one between *technical virtual power plant (TVPP)* and *commercial virtual power plant (CVPP)*, these two entities co-operate in order to achieve the VPP goals. In Figure 2.1 is possible to observe a scheme in which the data exchange between the different agents acting in a VPP is reported, particularly the role of CVPP and TCPP will be discussed in the next sub-session.

[1]DER: Distributed Energy Resources identify a generation, storage or DR unit located near to the final users; they are not able to directly partecipate to the electrical market due to their contained sizing power.

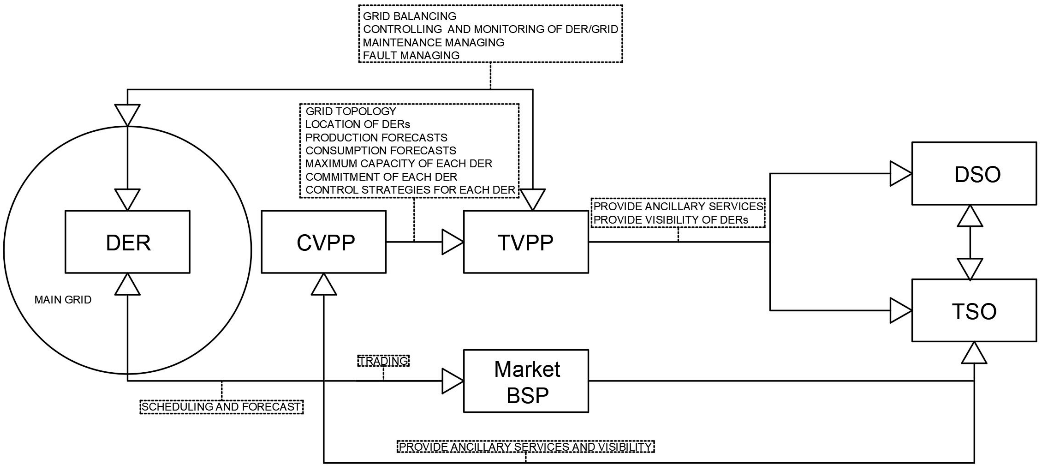

Figure 2.1: Architecture of a VPP, data exchange

2.2.0.1 Technical virtual power plant

The TVPP is responsible for the correct management of the power flows inside the VPP between all the different DER , the correct execution of the VPP services and the continuous monitoring of the VPP devices. To achieve this, it considers the following data that are provided by the CVPP:

- Grid topology;
- Location of the DERs;
- Production and consumption forecasts;
- Maximum capacity and commitment of each DER;
- Control strategies for each DER according to contractual obligations.

Knowing these information the TVPP has to carry out the following tasks:

- Provide to DERs visibility at distribution and transmission level;
- Balance and manage the network executing the ancillary services;
- Monitor continuously the DER and the whole aggregate to retrieve hystorical data.
- Monitor and mange the fault, identifying the location;
- Manage maintenance.

2.2.0.2 Commercial virtual power plant

The CVPP considers the DER as commercial entities, its main role is to economically optimize the utilization of the VPP, this can be done managing the DER according to production and load forecasts together with a trading activity in the electricity market. CVPP constitutes bilateral contracts with both the distributed generation and the costumers sending the information about the negotiated quantities to the TVPP that will use them to correctly perform the power flow computation. A CVPP has also the important role of letting small DER units visible to the electricity market, allowing them to supply ancillary services. The CVPP functionalities can be summarized in the following way:

- Provide visibility to DERs in the electricity market;
- Trading in the wholesale electricity market;
- Scheduling of DER and demand profiles based on weather and load need forecasts;
- Providing of services to the system operator;
- Manage maintenance, costs and characteristics of DER.

Particularly a CVPP has to interact with:

- DER: in order to match generation with consumption profile, results have to be sent to the TVPP;
- BRP: it is a trading entity that makes a production/consumption plan available to TVPP;
- TSO: its role is to manage the main electrical system, keeping the instantaneous balance between demand and generation;
- TVPP: its role is to consider the CVPP submitted information in the power flow optimization of the VPP.

Three main concepts have to be remarked in this chapter, they are fundamental in order to fully understand the strength of the VPP technology, they are:

1. A VPP is constituted by different DERs, this means that is possible to mix together the advantages of different technologies, exploiting the synergies between them. Particular importance for this purpose is covered by the so called load-shifting; this allows to shift a load or a process from a certain period of the day to another one. For example, a dishwasher that normally runs from 6 to 8 p.m can be moved to operate from 9 to 11 p.m. This can be very useful when

applied to a large number of loads, in fact it may help in peak-load resolution or in solving grid congestions. Another example of synergy between different appliances can be given looking at the achievable advantages from exploiting the different time constants of thermal and electrical storages, a common example is given by the operation of combine heat and power plants (CHP) that can produce heat and electrical energy; thanks to storage systems it is possible to decouple the usage of thermal and electrical energy, this allows to have a degree of freedom more that can be exploited according to system operation purposes.

2. A VPP can be displaced in different geographical zones. Oppositely to micro-grids, the main goal of a VPP is to provide ancillary services to distribution and transmission system, having the possibility to displace it over a wide geographical region allows to formulate better trading strategies for the electricity market participation.

3. A VPP allows visibility of small DERs in the electricity market. Without the VPP structure, a large amount of DERs would be completely transparent to the electricity market. Demand Response is therefore strictly related with the aggregation concept and could not be largely and deeply exploited without it.

2.2.1 VPP all over the world

There are many examples of Virtual Power Plants all over the world, they are mainly installed or under installation in America, Australia (Adelaide) and Europe (Germany and Scotland). With the goal of a better comprehension a VPP example is now reported, particularly the analysis of a so called *living lab smart grid* installed in the Netherlands is briefly presented [8]. In this VPP, which is not a multi-site one, 25 households are interconnected, the VPP is managed in order to accomplish different goals that can be summarized in the following way:

- In-home optimization: this means that each consumer operates its own system in order to achieve the highest profits from regulating the power flow from/to the grid. This can be easily done looking at the energy prices, selling it when they are high while buying it when they are low. Of course, if a transport tariff is introduced, the logic of each user will change, since now the goal will be to consume the in-home produced energy rather than transporting it because of the economical losses imputable to the energy transportation;

- Technical coordination with the distributor: this is very important since the distribution network is continuously facing an increase of peak power demand. Many times, this potential overload leads to the need of new distribution lines just to face congestions; this can be potentially very expensive and may have a very negative environmental impact. For this reason, the capability of a VPP to regulate the absorbed or injected power in the distribution network is of paramount importance and can be performed thanks to the interconnection between all the devices inside the VPP;

- Commercial coordination with the market: this is the goal that mostly exploits the potentialities of a VPP. In fact, thanks to flexible devices, it is possible to optimize the bidding strategies in energy markets, actively participating to solve network imbalances and decrease peak power demand.

In order to achieve the presented goals a very high coordination level between all the appliances inside the VPP have to be reached, particularly in this installation the flexibility is gained thanks to:

- CHP - Combined Heat Power, installed in half of the households together with an heat storage system;

- mini Gas Turbines, can be installed next to CHP;

- RES - Renewable Energy Sources, they are solar (in each household) and wind (a turbine for the whole aggregate) power plants;

- DR - Demand Response, achieved through smart appliances as dishwasher, washing machine etc;

- ESS - Energy Storage System, it is provided by electric vehicles and in-home electricity storage.

All these devices are connected at the same main server through different concentrators, that are common points for sub-groups of devices. For instance all the households are connected to the same concentrator that receives set of data from all the households and send out to the main server an aggregate data-set representative of all the households; in the same way, all the electric vehicles are connected to another concentrator and supply to the main server an aggregated data-set relative to all the vehicles. This structure allows a scalable architecture for the VPP, allowing to manage a high quantity of units and data in relative short times with respect to a structure in which concentrators are not present and all the units send their data to the main server directly.

The just presented VPP has been reported since it is a representative example of the many different devices that can be involved in its structure and of the many different objectives that can be imposed to it.

2.2.2 VPP in Italy

Italy is a little bit behind on the VPP front and relevant installations cannot be found. Focusing on some small but relevant pilot projects it is possible to highlight two of them: in 2016 in Ciminna (Sicily) and in Codrongianos (Sardinia) 2 MW/2 MWh storage systems have been installed by ENGIE EPS (only EPS at that time) in collaboration with Terna. The objective of this project, named *Storage Lab*, is to study how to increase the security of the electrical transmission system of Italian islands thanks to storage systems that are able to rapidly face the unbalances caused by the unpredictable behavior of RES. Once the project will be completed the overall installed capacity will be of 16 MW of different storage technologies, allowing to identify a posteriori the best technology to be applied for these purposes. In fact, the *Storage Lab* is just the experimental phase of a larger project that involves a total installed capacity of 40 MW. Another project, named *Large Scale Energy Storage Project,* has been promoted by Terna; in this case the installed capacity will be of 35 MW installed in Ginestra (12 MW), Flumeri (12 MW) and Scampitella (10.8 MW) that are located in Campania (Italy); the goal of the project is to increase the security of an HV transmission line that due to high RES production frequently experiments congestions; after a trial and tuning phase with on-site monitoring the storage systems are currently operating in remote control since 2015. In Figure 2.2 the installation sites of the presented pilot projects are reported.

Figure 2.2: Installation site of storage pilot projects

Both these projects can be seen under the VPP point of view if we consider them as an aggregate of DER (in this very case, energy storage systems) used in order to provide stability and quality to the national transmission system. However, it is easy to realize that these projects are not exploiting entirely the benefits achievable from a VPP, in fact they are not constituted by different DERs and therefore they cannot rely on the benefits coming from the previously mentioned synergies between them. The most relevant event regarding VPPs in the Italian scenario occurred in 2017: Italian TSO promoted some pilot projects in order to let new participants entering in the ancillary services market and face in this way the increasing MSD cost trend. These projects have the common goal of combining many not enabled units in order to create an enabled aggregate for the MSD market participation. Depending on the type of plants installed in the aggregate it is possible to distinguish between:

- UVAC: Virtual unit enabled to consumption;
- UVAP: Virtual unit enabled to production;
- UVAM: Mixed virtual enabled unit;
- UVAN: Nodal virtual enabled unit.

These virtual units can be looked as VPP, even if their are subjected to particular constraints. In the next chapter, the key points of the regulatory documents published by TERNA for each pilot project will be reported.

Chapter 3

Terna Pilot Projects

Following the Decree 300/2017/R/eel [2], the Italian ancillary services market became attractive for new participants, as Terna set the first opening of the market to electrical demand, new production units (including the renewable ones) and storage systems. The enabled users for MSD participation before and after this decree are reported in Figure 3.1 and 3.2 , it will be seen that this simple scheme actually will be the starting point for a radical change in the strategies adopted in the electricity market.

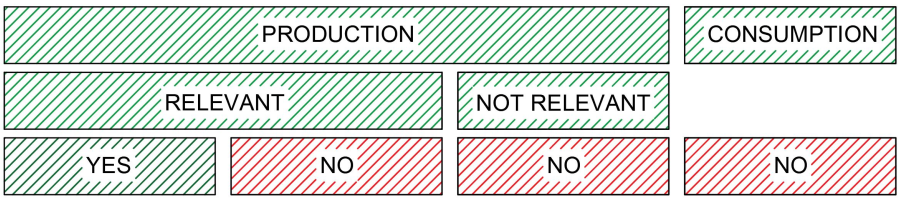

Figure 3.1: Enabled units, ante Decree 300/2017/R/eel

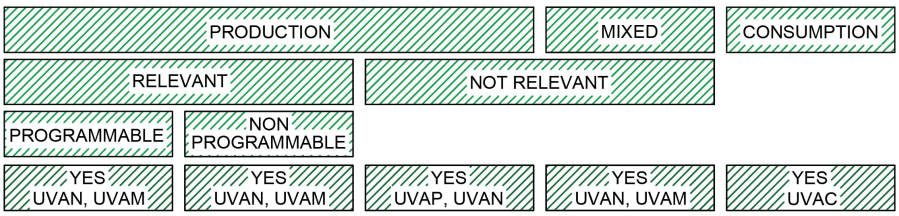

Figure 3.2: Enabled units, post Decree 300/2017/R/eel

In particular, 4 pilot projects were instituted, namely:

1. UVAC - Virtual units enabled to consumption;
2. UVAP - Virtual units enabled to production;
3. UVAM - Mixed virtual enabled units;

4. UVAN - Nodal virtual enabled units.

It is important to highlight how this decree just presents and initiates pilot projects. In the last year some key events occur, introducing specific rules to which they are subjected. A timeline is reported to highlight these events in Figure 3.3.

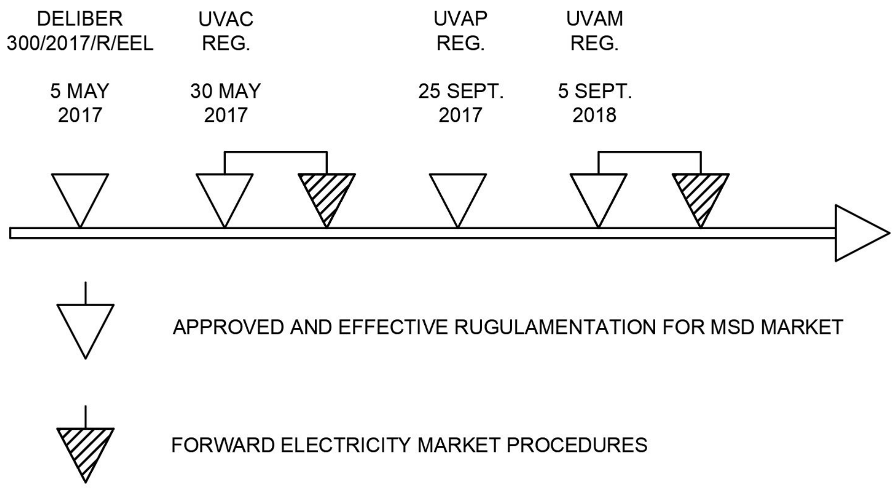

Figure 3.3: Timeline of important dates regarding UVA

In the following sections these pilot projects will be analyzed based on the documents presented in the timeline; for this purpose, it is important to introduce the terminology that will be adopted:

- UVA: Virtual enabled unit;

- BSP: Balancing Service Provider, it is the owner of the UVA and the responsible for offering ancillary services to the grid operator;

- BRP: Balance Responsible Party, it is responsible for the payment of the effective imbalances of the units belonging to the UVA, it manages their MGP and MI programs which result modified due to MSD participation;

- Aggregation perimeter: Terna defines precise perimeters for the constitution of a UVA, which are reported in Figure 3.4 through different colors.

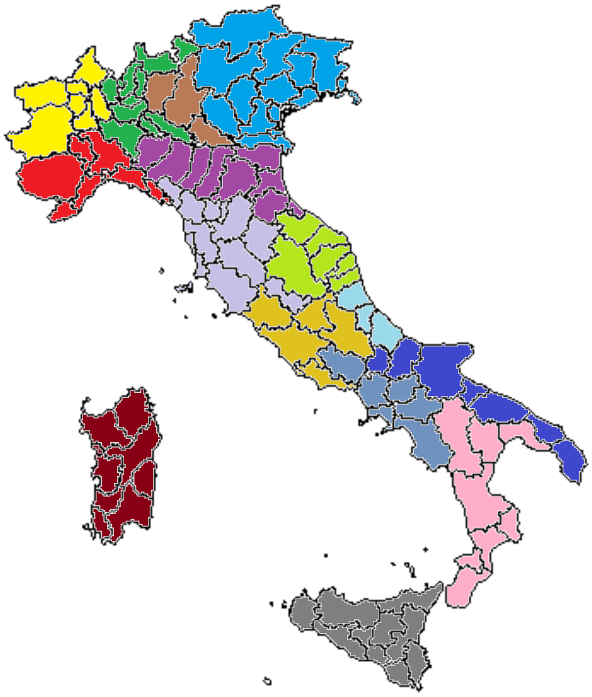

Figure 3.4: Aggregation perimeters for UVA constitution

The reference documents previously mentioned are the ones that report the definition and requirements for UVA creation ([3, 9, 10], respectively for UVAC, UVAP and UVAM) and the ones presenting the forward MSD market rules for UVA ([4,11], respectively for UVAC and UVAM).

3.1 UVAC

3.1.1 Definition and requirements

A UVAC can be constituted by many different consumption points connected at high, medium or low voltage systems. For each of these points, it is mandatory to provide hourly measures. Moreover, the following requirements must be satisfied:

- every consumption point of the UVAC has to be included in the same aggregation perimeter;
- no consumption point have to be listed on the AU (Acquirente Unico)[1] ancillary services contract;
- every consumption point has to install a monitoring device (UPMC), which has to be a able to send measures with a maximum time step of four seconds to a remote control center;

[1]Single Buyer (AU) is a company created by GSE with the task of guaranteeing the availability of electricity to cover the demand of final consumers that buy electrical energy from the local distributor.

- UVAC is relevant only for the ancillary services market, not for the energy market.

From a technical point of view is also required that:

- Maximum controllable power has to be not lower than 1 MW (initially this limit was of 10 MW);
- The increase of the power injection must occur within 15 minutes from TERNA dispatching order and the variation must be maintained at least for 3 consecutive hours.

The power injection increase into the grid has to be considered as a power withdrawn decrease from the consumption units inside the UVAC.

3.1.2 Obligations for UVAC owners

UVAC can supply the following ancillary services:

- increasing replacement tertiarty power reserve;
- real time balancing.

Each UVAC owner has to:

- constitute a physical control centre that receives orders from Terna and redistributes them to all users. This physical centre has to install all the necessary devices and software in order to guarantee the communication between the control centre and the UVAC units;
- present a standard offer to be used in case the daily offers are not presented;
- optionally present a daily offer during the MSD ex-ante session;
- optionally present an improved daily offer for the MB market with respect to the MSD ex-ante session, if no offer is presented for MB the one of the MSD ex-ante will be used.

The presented selling offer is a unique combination of quantity and price.

Furthermore, UVAC pilot projects also allow North and North-Centre aggregation zones to participate to a forward ancillary services market. In this case, the UVAC has to take part to a dutch auction in which it must provide an offer comprehensive of a maximum capacity (MW) and a premium price (k€/MW/year)[2].

[2]Regarding the last activated pilot projects the premium price starting value was of 30 k€/MW/year.

Auction closing establishes the selected units and the relative combination of (premium[€/MW/year],assigned capacity[MW]). The premium corresponds to the premium presented by the UVAC (pay-as-bid) while the assigned capacity can be lower or equal to the maximum capacity presented by each unit. Each UVAC has to respect particular constraints to participate to the forward ancillary services market:

- it has to present offers for both balancing and tertiary reserve;
- the offered quantity has to be equal to the assigned capacity;
- the offer duration has to be of at least three consecutive hours between 2 p.m and 8 p.m for each day of the week but Sundays and Saturdays;
- the offers have to respect the rules reported on *grid code - chapter 4* [12];
- the offer price cannot be higher than a fixed Strike Price [€/MWh][3].

The presentation of these offers does not force Terna to their acceptance. The TSO verifies the correct execution of the dispatching order with reference to the energy exchanged by the aggregate in the 15 minutes before the order communication.

3.1.3 Service remuneration

The remuneration follows the same rules adopted for the enabled units presented in [13]; in each quarterly hour period of the dispatching order the remuneration equals the product between the accepted quantity and the offered price. In particular:

- the accepted quantity equals the quarterly average value of the modulation profile required by Terna;
- the offer price equals the price offered for the hour interval which includes the considered 15 minutes period.

If the dispatching order is not correctly executed, the BSP has to pay the TSO a penalty equal to the 150% of the offered MSD price multiplied by the difference between the dispatched and the produced quantity.

With reference to the forward ancillary services market, two different remunerations can be distinguished: a fixed one and a variable one. The former does not depend on the offer being accepted; from the fixed remuneration, which is equal to the premium price, it is possible to retrieve a daily fixed remuneration (d.f.r), that is a value monthly differentiated, computed as:

$$d.f.r = \frac{fixed\_remuneration}{12 \cdot Nm} \tag{3.1}$$

[3]Regarding the last activated pilot projects the Strike Price was of 400€/MWh.

where Nm takes into account all the days in a month "m" but Sundays and Saturdays.

The BSP receives from Terna the product between d.f.r and the assigned quantity for the days in which the offer obligations have been respected. The d.f.r can be linearly increased up to 200% if the offers are formulated at least for the assigned quantity in every hour between 2 p.m and 8 p.m. Concerning the variable remuneration, only the accepted offers are remunerated following the rules reported on the *grid code-chapter 7 [13]*. For the fixed remuneration, if the offer do not respect the required characteristics for more than the 70% of the validity period the fixed remuneration is not given to the BSP for the whole validity period.

3.2 UVAP

3.2.1 Definition and requirements

A UVAP can be constituted by many injection points connected at high, medium or low voltage, which must provide hourly measures. Moreover, the following requirements have to be satisfied:

- every injection point of the UVAP has to be included in the same aggregation perimeter;
- no injection point has to be listed on the GSE ancillary services contract;
- every injection point has to present a monitoring device (UPMG), which has to be able to send measures with a time-step of 4 seconds to a remote control center;
- UVAP is only relevant for the ancillary services market, not for the energy market.

From a technical point of view, the UVAP is also required to:

- have a *maximum control power* and a *lower minimum control power* higher or equal to 1 MW in absolute value if it is enabled both for increasing and decreasing power services (initially this value was 5 MW);
- have a *maximum control power* higher or equal to 1 MW and a *lower minimum control power* equal to 2 kW if it is just enabled for increasing power services;
- have a *lower minimum control power* not lower than -1 MW and a *maximum control power* equal to 2 kW if it is just enabled for decreasing power services;
- increase or decrease the power injection within 15 minutes from TERNA dispatching order and keep the variation for at least 3 consecutive hours.

3.2.2 Obligations for UVAP owners

UVAP can supply the following ancillary services:

- increasing and/or decreasing replacement tertiary power reserve;
- increasing and/or decreasing real time balancing;
- congestion relief during program phase throughout the acceptance of increasing and/or decreasing offers.

Each UVAP owner has to:

- constitute a physical control centre that receives orders from Terna and redistributes to all users. This physical centre has to install all the necessary devices and software in order to guarantee the communication between the control centre and the UVAP unities;
- execute dispatching orders as regulated in chapter 4 of Terna grid code [12] for enabled units; therefore, up to 3 and 4 combinations of quantity and price can be presented respectively in MSD ex-ante and MB;
- present a baseline that is the total power profile of the whole units belonging to the UVAP with a 15-minutes resolution, which will be used by Terna in order to verify the correct execution of the dispatching orders[4].

The presentation of these offers does not force Terna to their acceptance.

3.2.3 Service remuneration

The remuneration follows the same rules adopted for the enabled units presented in [13]; in each 15-minutes period of the dispatching order the remuneration equals the product between the accepted quantity and the offered price. In particular:

- the accepted quantity equals the average value in the 15-minutes period of the modulation profile required by Terna;
- the offer price equals the price offered for the hour interval including the considered quarter of hour.

If the baseline is not respected a penalty equal to 2% of monthly BSP MSD incomes is applied.

[4]The baseline can be modified until the end of each MSD ex-ante sub-session

3.3 UVAM

3.3.1 Definition and requirements

A UVAM can be constituted by:

1. An aggregate containing one or more of the following elements:
   (a) not relevant production unit (UP);
   (b) consumption unit, including the interruptible ones but the ones already used in interruptibility contracts;
   (c) stand alone storage plants or alternatively storage plants coupled with not relevant production and/or consumption units, i.e. allowing the first opening to the Vehicle To Grid technology (V2G);
   (d) Relevant production units whose maximum power injection into the grid is 10 MW and that are not yet mandatorily enabled to MSD and share the grid connection point with consumption units (excluding the auxiliary services) and eventually with non relevant production units and/or storage systems;
2. One or more production units whose power injection into the grid is higher than 10 MW and that are not yet mandatorily enabled to MSD and do not belong to the previously mentioned category (1.d) which shares the grid connection point with consumption units (excluded auxiliary services) and eventually with non relevant production units and/or storage systems.

All the injection and/or consumption points are subject to the following constraints:

• All the points connected to the UVAM have to be localized in the same aggregation perimeter;

• All the consumption units of the UVAM have not to be listed in a UCMC[5];

• No consumption point of the UVAM has to be listed on the AU ancillary services contract;

• Every injection point has to present a monitoring device (UPM), which has to be able to send measures with a 4-seconds time-step to a remote control centre;

• For the units belonging to the previously mentioned point 2, the average absorption of the consumption units of the UVAM has to be at least 50% of the energy produced by the UVAM production units.

From a technical point of view, it is also required that:

• If the UVAM is enabled both for increasing and decreasing power services it has to be characterized by a *maximum enabled power* and a *minimum enabled power* not lower, in absolute value, than 1 MW;

[5]UCMC: Consumption units enabled for capacity market.

• If the UVAM is enabled just for increasing power services, the *maximum enabled power* has not to be lower than 1MW while the *minimum enabled power* has not to be lower than 2 kW;

• If the UVAM is enabled just for decreasing power services, the *minimum enabled power* has not to be lower than 1MW in absolute value while the *maximum enabled power* has not to be lower than 2 kW in absolute value;

• The power variation has to occur within specific time limits depending on the dispatching service that is given by the UVAM, as it will be discussed in the next section. UVAM are relevant both for the ancillary services market and the energy market, therefore a new constitution dispatching point is associated to them.

3.3.2 Obligations for UVAM owners

UVAM can supply the following ancillary services:

1. congestion relief during program phase through the acceptance of increasing and/or decreasing offers.
2. increasing and/or decreasing spinning tertiary power reserve;
3. increasing and/or decreasing replacement tertiary power reserve;
4. increasing and/or decreasing real time balancing;

With reference to the specific ancillary service the UVAM has to vary its power as reported:

- within 15 minutes from receiving the dispatching order for services 1, 2, 4;
- within 120 minutes from receiving the dispatching order for service 3.

This variation has to be kept for:

- 120 minutes for services 1, 2, 4;
- for 480 minutes for service 3.

Finally, with reference to the increasing services named 1, 2, 3, the only enabled UVAM will be the ones that present a non-programmable, modulable power production lower than the 40% of the maximum enabled power.

Each UVAM owner has to:

- constitute a physical control centre that receives orders from Terna and redistributes to all users; this physical centre has to install all the necessary devices and software in order to guarantee the communication between the control centre and the UVAM units;

- present a predefined MSD ex-ante offer to be inserted in Terna systems that would be used if no daily offer is provided;
- present a daily offer to substitute the predefined one for MSD ex-ante;
- update the MSD ex-ante offer presenting an improved MB offer;
- execute dispatching orders as stated in *chapter 4* of *Terna grid code [12]* for enabled units;therefore, up to 3 and 4 combinations of quantity and price can be presented respectively in MSD ex-ante and MB, and MB offers can just be an improvement of the MSD ex-ante ones;
- present to the TSO the quarterly baseline that represents the cumulative power profile of the UVAM after deduction of the loads subject to the instantaneous interruption service. It has to be presented for each sub-phase of the programming phase of MSD within the end-time for technical data communication of enabled unites as reported in *grid code [12].* Afterwards, the quarterly baseline can be updated in each sub-phase of MSD programming phase within the end-time for the presentation of the same sub-phase technical data. The baseline is then used by Terna to verify if the dispatching orders have been correctly executed;
- communicate to Terna how the power produced for a given dispatching order has been sub-divided among different participants of the UVAM so that Terna can modify the post-MI programs for each of them.

UVAM pilot projects provide also the possibility to participate to a forward ancillary services market. In order to participate to this market a UVAM has to take part to a dutch auction providing an offer constituted by a maximum capacity (MW) and a premium price (k€/MW/year)[6]. Auction closing provides the selected units with the relative combination of premium [€/MW/year] and assigned capacity [MW]. The premium corresponds to the premium presented by the UVAM (pay-as-bid), while the assigned capacity can be lower or equal to the maximum capacity presented by each unit in the offer. Each UVAM has to respect particular constraints to participate to the forward ancillary services market, in particular:

- present increasing offers for balancing and tertiary replacement reserve in MSD ex-ante and for balancing in MB market;
- the offered quantity has to be at least equal to the assigned capacity;
- the offer duration has to be at least four consecutive hours between 2 p.m and 8 p.m for each day of the week but Sundays and Saturdays;

[6]The premium price Cap is of 30k€/MW/year

- offers have to respect the rules reported on *grid code -chapter 4* [12];
- The offer price cannot be higher than a fixed Strike Price [€/MWh][7].

The presentation of these offers does not force Terna to their acceptance; the TSO can verify the feasibility of the presented offers by the BSP.

3.3.3 Service remuneration

The remuneration follows the same rules adopted for the enabled units. In particular, Terna defines:

- the accepted quantities and their remuneration regarding the programming phase of MSD as reported in *Terna grid code-annex 22* [14];
- the accepted quantities and their remuneration regarding the real time balancing phase of MSD as reported in *Terna grid code-annex 23* [15];

If the dispatching orders are not respected, BSP is subject to penalties that must be paid to Terna. Two scenarios can be distinguished for the penalties evaluation. The first one refers to a incomplete execution of a dispatching order, while the second one regards the opposite power variation between an interruptible unit and the dispatching order, namely a power injection increase request is faced with an interruptible load power decrease. In this case, there is an additional penalty term that must be taken into account. With reference to the forward ancillary services market, two different remunerations can be distinguished, a fixed one and a variable one. The former does not depend on the offer acceptance, as it is possible to retrieve from the fixed remuneration, which is equal to the premium price, a daily fixed remuneration (d.f.r in the next), that is a value monthly differentiated, computed as:

$$d.f.r = \frac{fixed\_remuneration}{12 \cdot Nm} \tag{3.2}$$

where Nm counts all the days of month m but Sundays and Saturdays.

The BSP receives from Terna the product between d.f.r and the assigned quantity for the days in which the offer obligations have been respected. Concerning the variable remuneration, only the accepted offers are remunerated following the rules reported in the *grid code-chapter 7 [13].* With reference to the fixed remuneration, if the offer do not respect the required characteristics for more than the 70% of the monthly period, the fixed remuneration is not given to the BSP for the whole considered month.

[7] Strike Price is of 400€/MWh

3.4 UVAN

For the UVAN, no regulatory document is available yet. In the present work they are just defined as UVA which can be constituted by:

• relevant production units not mandatorily enabled in MSD market, both programmable and not programmable;

• not relevant production units, both programmable and not programmable;

• consumption units. These units must be connected to the same national transmission node.

UVAN are relevant both for the ancillary services market and the energy market, therefore a new constitution dispatching point is associated to them.

3.5 Pilot projects results

In the following paragraphs, a brief summary of the pilot projects results is reported, with a particular focus on the data presented during July 9th, 2018 Terna meeting and *Electricity Market Report 2018.*

3.5.1 UVAC

UVAC pilot projects were lunched in the following periods:

- 19th July - 30th September 2017;
- 15th January - 31st March 2018;
- 18th June - 30th September 2018.

In these projects the Strike Price was 400 €/MWh with a premium price of almost 30 k€/MW/year. In Figure 3.5 the enabled power is reported along with the contractualized one for UVAC participation during the pilot projects running periods.The effectiveness of these projects is evident since the exchanged volumes are subject to a constantly increasing trend. In fact, it can be observed in Figure 3.6 that the enabled power supplied by purely consumption units reaches the 25% of the total enabled power; Concerning the reliability it can be noticed in Figure 3.6 that the 75% of the traded quantities on MSD market were actually supplied by UVAC, which is a significant result that allows to consider UVAC as actually capable of physically supply the traded quantities.

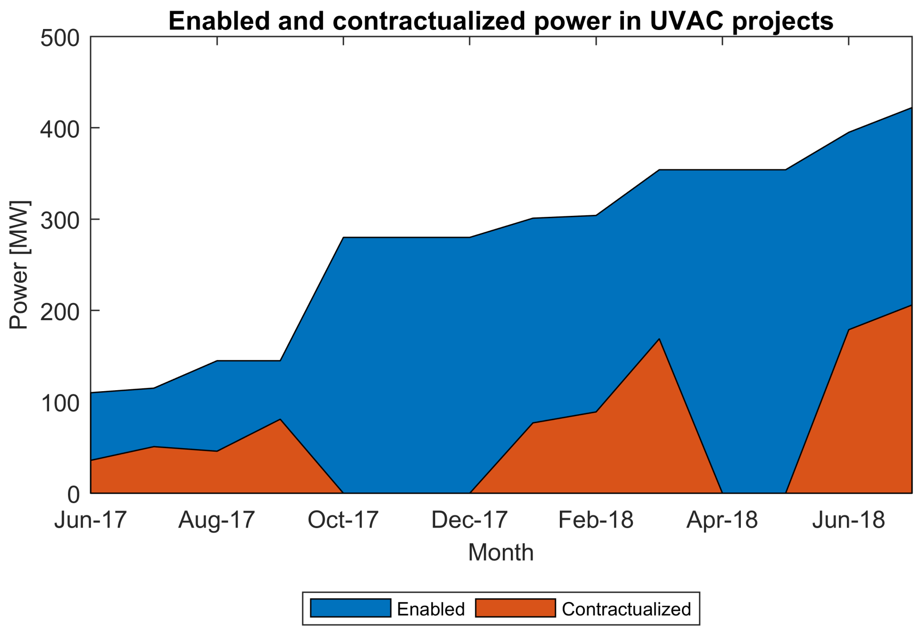

Figure 3.5: UVAC enabled and contractualized power

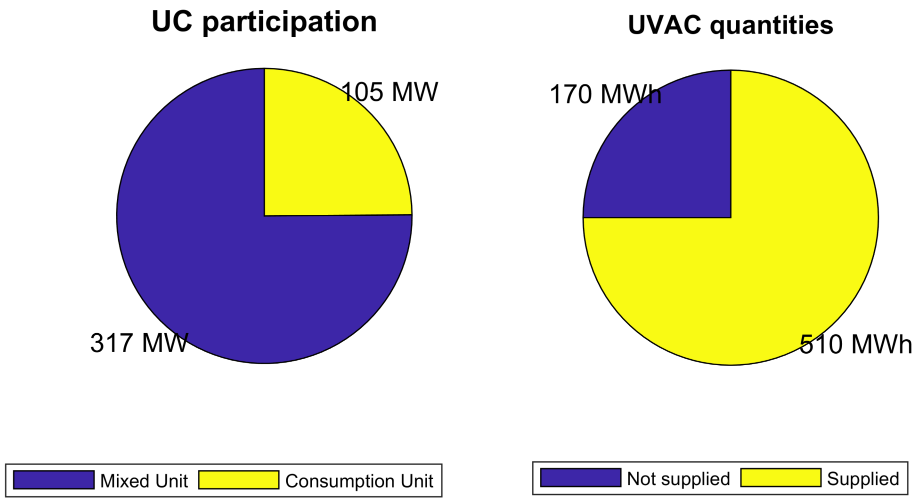

Figure 3.6: UVAC participation and reliability

A final consideration considering the operators that undertook these pilot projects: they were essentially utilities and traders, while smaller companies decided not to participate. This is mainly due to the fact that the former have a good knowledge of the market dynamics, while for the latter it is more difficult to have a proper understanding of these pilot projects and the opportunities they may create in the future.

3.5.2 UVAP

UVAP pilot projects can be observed in the period from December 17th, 2017 to June 18th, 2018. In Figure 3.7 the enabled power trend for UVAP participation is reported during the pilot project running period. Similarly to the UVAC, it is possible to highlight that the traded volumes continuously increase, nowadays the enabled power is almost of 100 MW; in particular it is reported in Figure 3.8 and it can be observed that almost the 27% can be linked to non-programmable energy sources. Concerning the reliability, in Figure 3.8 the quantity actually supplied in the running period for UVAP projects is reported with respect to the total traded one; it can be noticed that almost the 76% of the traded volumes on the MSD market have been supplied. The strategy adopted for UVAP pilot projects does not require a forward electricity market; this choice may have been taken in order to push the initial phase of the project. The effects of this choice can be noticed also in the traded quantities, much lower than the ones observed in the UVAP case.

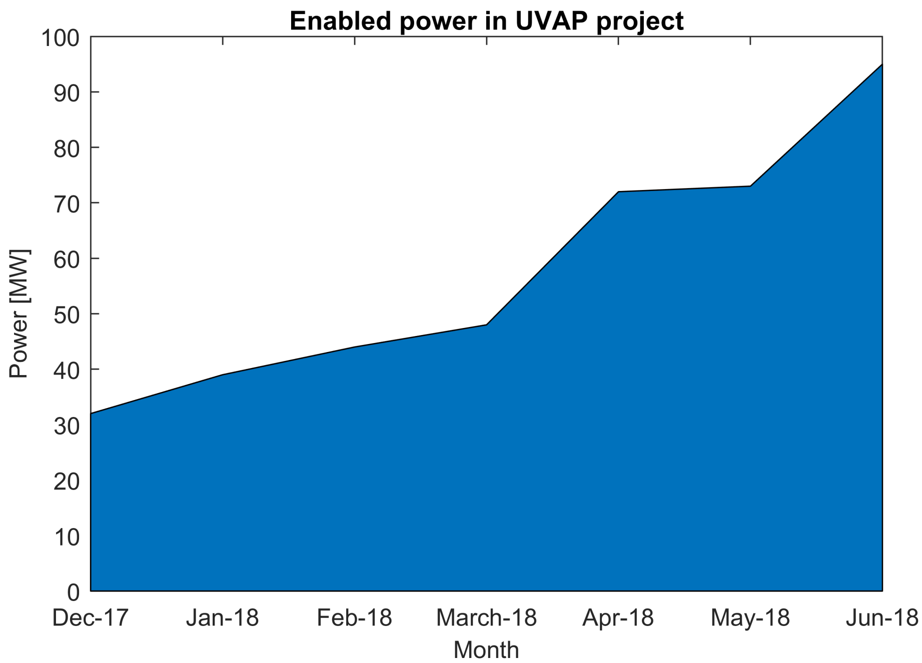

Figure 3.7: UVAP enabled and contractualized power

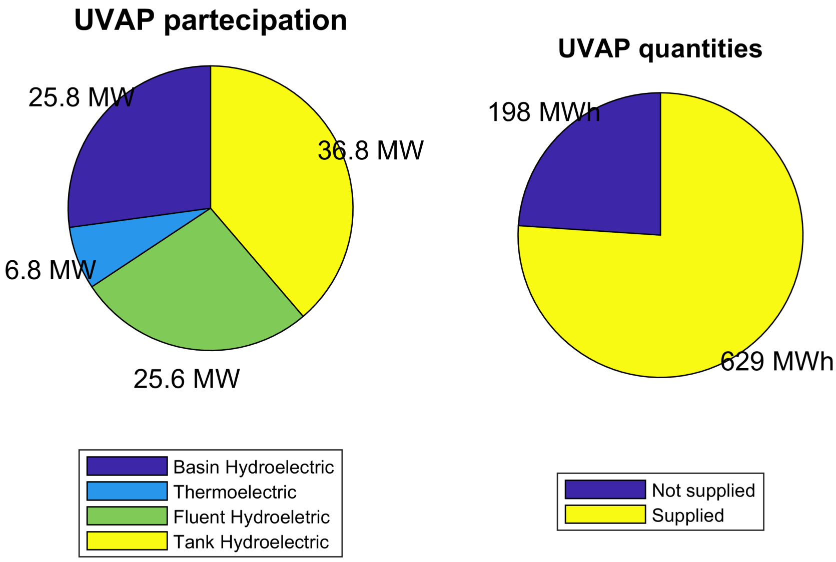

Figure 3.8: UVAP participation and reliability

Finally, it is important to highlight that no wind or solar power plants have participated in these project. This is not due to technical limitations nor to regulatory documents: the problem is just economical since these plants are not interested in curtailing their energy because of the high incentives that they can achieve. In fact, as an UVAP renewable plants may only offer a decrease in power injection, losing the incentives related to their power production and making the project unprofitable. Storage systems could be exploited in order to achieve an economical advantage from both increasing and decreasing power injection offers formulated by these plants, but nowadays they are not a common technology for these applications yet.

3.5.3 UVAM & UVAN

No results are available yet, regarding UVAM pilot projects have already been lunched, regarding the UVAN no information has been found.

Chapter 4

Balancing market analysis

In this chapter a deep analysis of the Italian balancing market is carried out along 2017; particularly, in order to perform this analysis a *market analysis tool* has been developed using the software MatLAB, which allows to collect, organize and manipulate electricity market data. The goal of this analysis is to obtain a global overview of the MB in order to understand which offers have been accepted and to formulate a possible strategy to be performed, optimizing the bids of a VPP that participates to this market as deeply presented in *chapter 5.* In the following, the method applied for data handling, structuring and analysis will be presented; finally, a statistical analysis will be done in order to find out which is the probability of a bid to be accepted in the market. Historical prices for MB have been downloaded from GME website [16].

4.1 Data organization

Downloaded data are saved in .xlm format, one file per day. Afterwards, the files have been converted and modified through an Excel macro, removing also the unnecessary information, in order to obtain a simplified .xlsx file which can be used as input sheet for the data analysis carried out in MatLAB. The structure of the document presents different fields and they are here reported:

- PURPOSE_CD: It is the typology of the offer, particularly:
  - BID: buying offer, meaning that the operator is buying energy from the grid;
  - OFF: selling offer, meaning that the operator is selling energy to the grid;
- TYPE_CD
  - STND: predefined offer, used if no current offer is presented;
  - REG: current offer;

- STATUS_CD
  - ACC: Accepted offer;
  - REJ: Rejected offer;
  - INC: Incongruent offer;
  - REP: Substituted offer;
  - REV: Revoked offer
  - SUB: Submitted offer;

  For the purposes of this thesis, only the accepted offers are relevant while, the other ones, are reported for the sake of completeness. With reference to the last four, no documentation has been found to report the differences among them. Anyway, they are not used for market resolution and not relevant for the correct evaluation of this work.
- MARKET_CD: it identifies the market session and phase (MGP, MI, MSD, MB)
- UNIT_REFERENCE_NO: identification code of the unity;
- INTERVAL_NO: reference hour of the offer;
- BID_OFFER_DATE_DT: date to which an offer is referred;
- TRANSACTION_REFERENCE_NO: identification code for GME;
- QUANTITY_NO: quantity offered by the operator [MWh];
- AWARDED_QUANTITY_NO: quantity accepted in the market [MWh];
- ENERGY_PRICE_NO: price offered by the operator [€];
- MERIT_ORDER_NO: offer merit order as computed by market resolution algorithm;
- ADJ_QUANTITY_NO: modified quantity by the GME [MWh];
- GRID_SUPPLY_POINT_NO: relevant exchange point to which a unit refers;
- ZONE_CD: market zone to which a unit belongs;
- AWARDED_PRICE_NO: price accepted in the marekt [€];
- OPERATORE: operator business name;
- SUBMITTED_DT: submission time of the offer;
- BILATERAL_IN: identify bilateral contractualized transactions;

- SCOPE: identifies the service to which the offer refers:
  - AS: minimum or shut-down;
  - RS: secondary power reserve;
  - GR1: step 1;
  - GR2: step 2;
  - GR3: step 3;
  - GR4: step 4;
  - AC: start - up;
  - CA: set-up modification;
- QUARTER_NO: quarter of hour relative to the hour specified in INTERVAL_NO
- BAType: no longer relevant since 2016, it assumes always the value NOREV indicating that an offer has been accepted in MB.

For the proposed analysis just a few of these fields have to be analyzed, namely: PURPOSE_CD; STATUS_CD; MARKET_CD; INTERVAL_NO; BID_OFFERED_DATE_DT; ENERGY_PRICE_NO; ZONE_CD; SCOPE; QUARTER_NO .

The obtained .xlsx files have then been uploaded in MatLab where a *timetable* structure has been created to easily manage the high number of yearly offers. This table is manipulated through a MatLab script that allows to carry out data reshaping, data plotting and statistical analysis.

4.2 Data manipulation

As mentioned, data have been handled developing a MatLab tool that allows to organize them following different aggregation criteria. Different analyses have been done for different market zones, for both offer purposes and for each scope. Data have been initially organized in order to obtain:

- representative week for the whole year;
- representative week for each month;
- representative week for each season.

These weeks retain the information about balancing market accepted offer prices; it is worth to recall that for MB market just GR scopes are the relevant ones and that data have been analyzed following two different approaches: firstly aggregating them accordingly to offer scope, secondly disregarding it. About the last mentioned evaluations, is important to realize that the offer scope is not relevant for the acceptance or rejection of an offer. In fact, its importance is only related to the specific unit which supplies the offer that can better discretized the offered power quantities relating them to different prices according to its own production costs. Regarding the data resolution a 15-minutes period has been considered, accordingly with bid intervals of MB market. Starting from the obtained representative weeks a statistical analysis regarding the accepted offers has been carried out. According to this analysis, it is possible to retrieve the probability of a given offer to be accepted in the MB market and the offer to present in order to be accepted in the market with a certain probability. All the obtained data are again represented aggregating and comparing them in representative weeks, following the above discussed structure. All these analysis will be better understood in the following sections thanks to graphical representation. In Figure 4.1 it is reported a sketch which schematically shows how data have been organized.

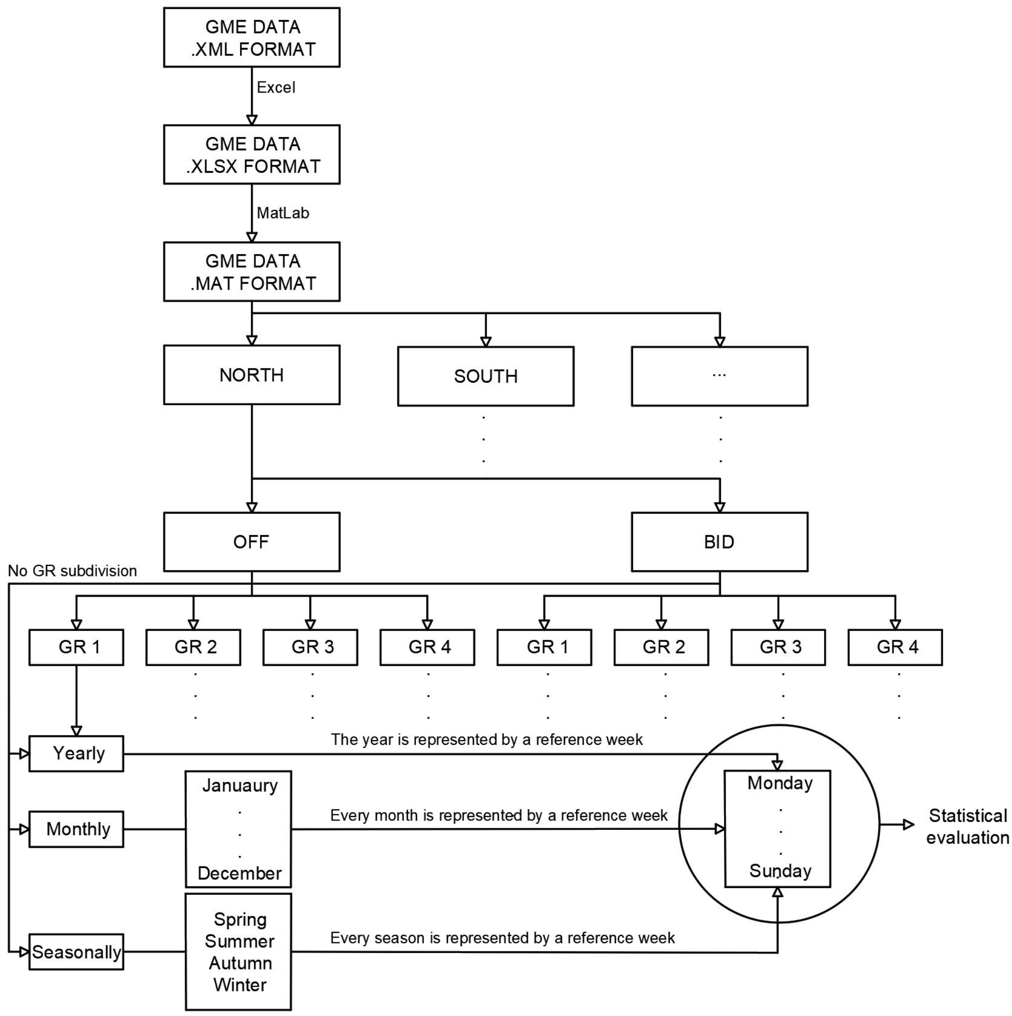

Figure 4.1: Data organization structure

4.2.1 Statistical evaluation

As mentioned in the previous paragraph, the accepted offers in the balancing market have been analyzed. Before continuing with this chapter, it is necessary a brief preview of what will be presented in *chapter 5*. In fact, the VPP considered in this work includes several residential and commercial units, which allow to operate *demand response*, implementing an optimal bidding strategy for the balancing market. Literature presents different examples of bidding strategy of a unit in the MB, among which the most common is analysing historical MB data (one year period for example) and for each relevant period finding out which is the maximum price of the accepted offers; then, if an offer is presented, for that relevant period, having a lower value with respect to the historical maximum one, the offer is considered accepted, otherwise it is considered rejected. In this final dissertation a different approach has been adopted; in fact, basing the acceptance or the rejection of an offer only on the fact that this offer is higher or lower of a certain value seems to be not the best adoptable strategy. In order to understand the reasons behind this consideration, figure out that for a given relevant period 5 offers occur, 4 of them are contained in a range that goes from 10 €/MWh to 200 €/MWh while the last one is of 500 €/MWh; according to the approach presented in literature, an offer of 400 €/MWh is accepted for that relevant period. However, this method does not take into account the fact that the majority of the offers are contained between 10 €/MWh and 200 €/MWh and therefore that the absence of the 500 €/MWh offer would led to the rejection of the 400 €/MWh offer letting the nearest accepted offer be 200 €/MWh, which is quite far from the initial 400 €/MWh value. For this reason a statistical analysis has been carried out that takes into account not only the maximum offer value but also for the number of offers occurring in a certain range of values. The guidelines for this evaluation have been taken from [17] where MSD ex-ante results have been considered. Relatively to this work, instead, MB results have been studied; since in the GME website no information about MB presented offers is available apart from the accepted ones, a complete statistical analysis as presented in [17] has not been carried out. However, exploiting the kernel estimation of the probability density function (KDE) A, easily implementable in MatLab, the probability density function (p.d.f) of the accepted offers has been analyzed. In Figure 4.2 it is possible to observe an example representing the obtained result concerning the evaluation of the accepted offers p.d.f in the first quarter of the second hour of the average Monday in 2017 with reference to North market zones OFF offers.

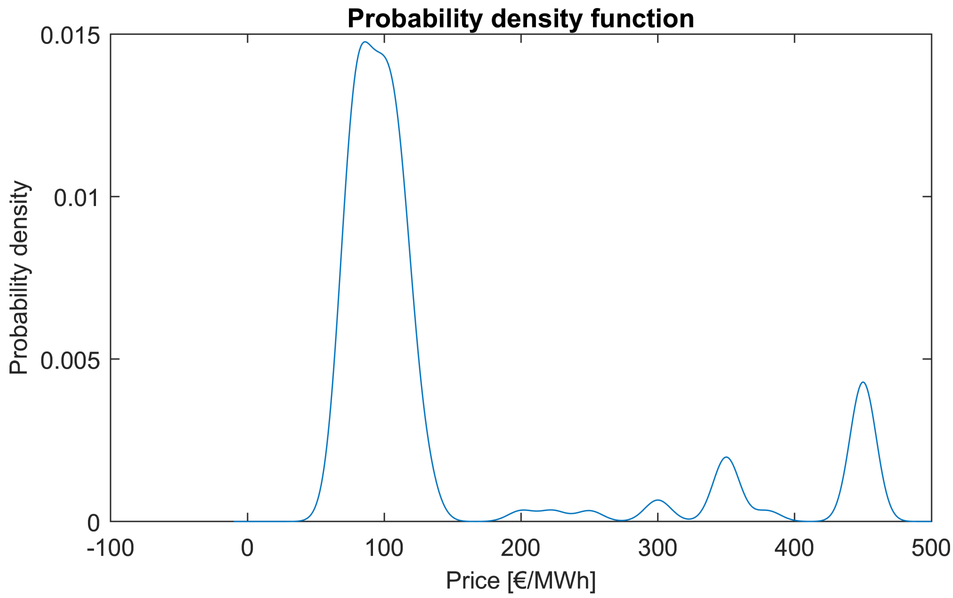

Figure 4.2: p.d.f Monday, 2017, 01.00am:01.15am, North, OFF

For the sake of a better comprehension of the mentioned advantages related to the usage of a KDE function A, also the histogram that accounts for the number of accepted offers subdividing them by predefined price ranges is reported in Figure 4.3.

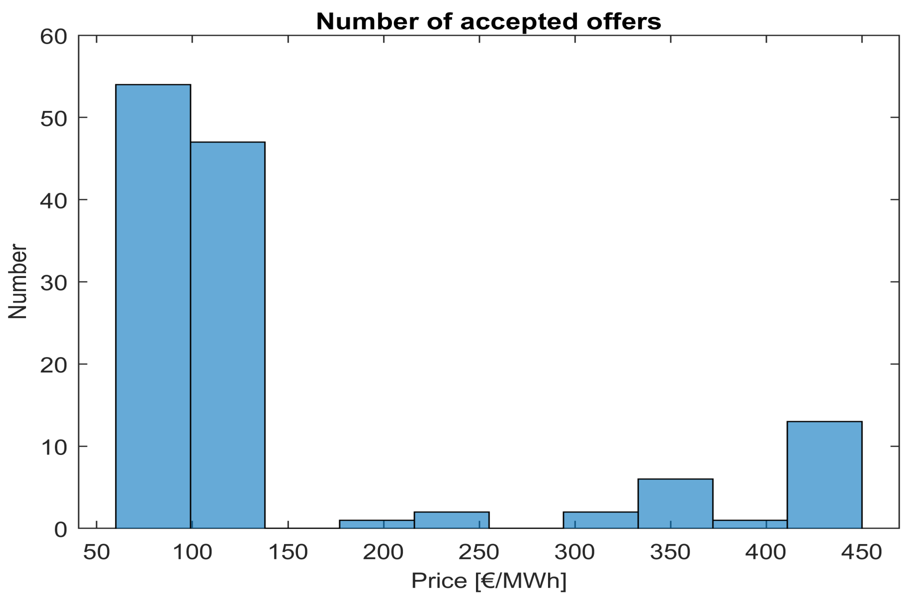

Figure 4.3: Histogram, Monday, 2017, 01.00:01.15, North, OFF

It is trivial to realize that the probability of an OFF offer to be accepted in the market is directly related to its economical value, meaning that the lower the value, the higher the acceptance probability; on the other hand the BID offers will behave in the opposite way, meaning the higher the offered price, the higher the probability to be accepted in the market. The just mentioned consideration can be taken into account through the cumulative probability density function which is reported in Figure 4.4 for the same example previously represented.

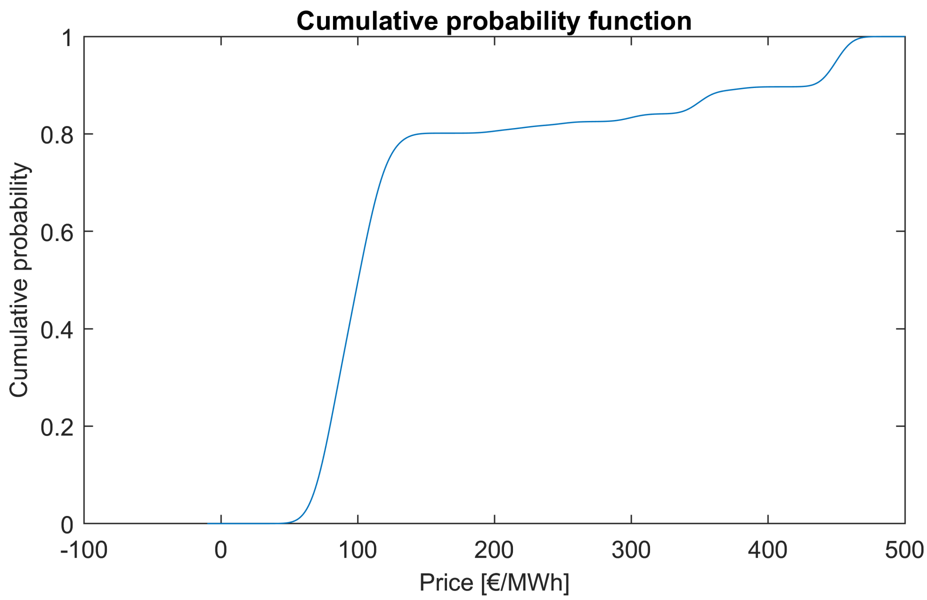

Figure 4.4: Cumulative p.d.f, Mondays, 2017, 01.00:01.15, North, OFF

This function identifies the probability to observe accepted offers with a value lower than a certain price. For what concerns the OFF offers, if the complementary function of the cumulative probability density function is computed Figure 4.4, the acceptance probability of an offer is obtained; correctly, a lower price matches with an higher probability of being accepted. On the other hand, for what concerns the BID offers, the behavior is the opposite since a lower price takes to a lower acceptance probability, as it can be observed in Figure 4.6. Actually, the previous retrieved characteristics identify price-probability couples in which the price is not exactly the one that should be used in order to exploit economical analysis. The reason is that this is a price evaluated only with reference to accepted quantities and does not takes into account which is the whole set of presented quantities; in other words it does not account for a real acceptance probability since it is evaluated only on the accepted quantities. In any case, in this work, this price is adopted also for economical analysis keeping in mind that the real price would be slightly different.

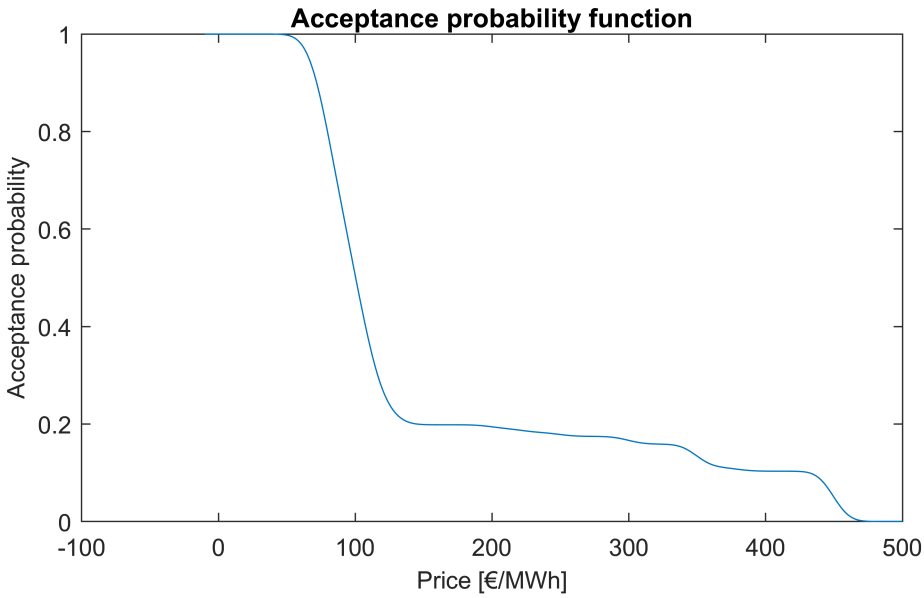

Figure 4.5: Acceptance p.f, Monday, 2017, 01.00:01.15, North, OFF

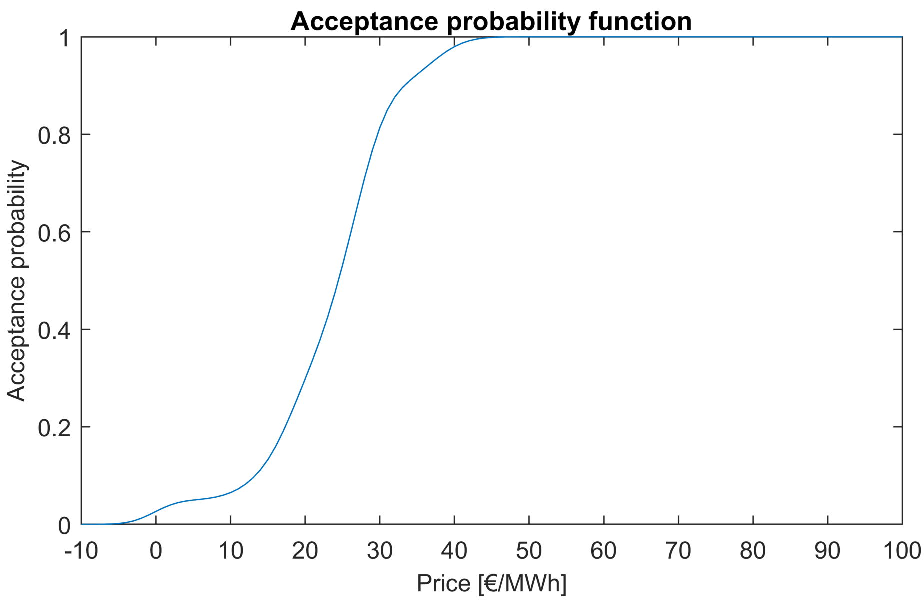

Figure 4.6: Acceptance p.f, Monday, 2017, 01.00:01.15, North, BID

This last result is the fundamental point from which the remaining evaluations have been accomplished, as it allows to identify the acceptance probability of certain offer presented at a given time interval as shown in Figure 4.7 for an OFF offer (80 €/MWh) and in Figure 4.8 for a BID one (30 €/MWh).

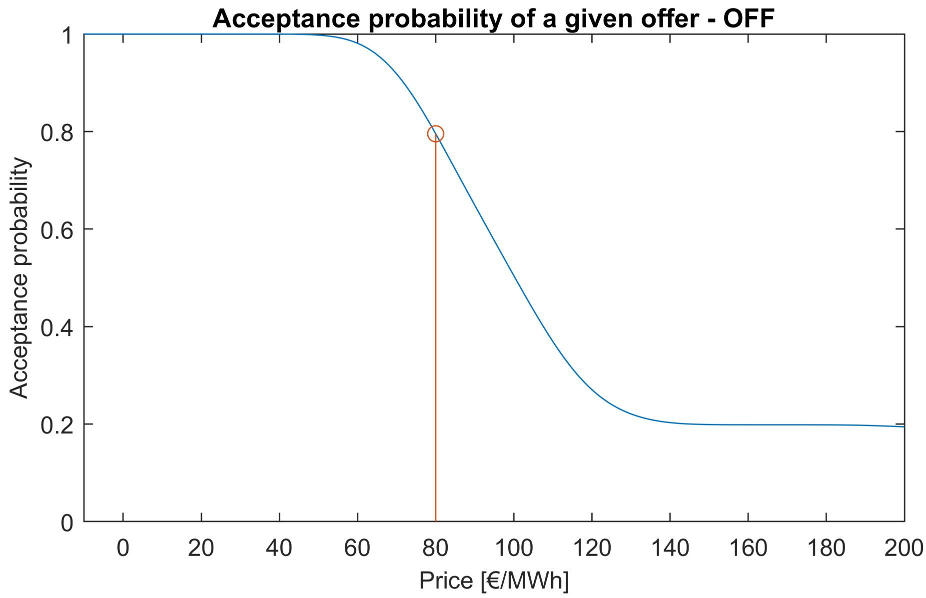

Figure 4.7: Acceptance p.f of an offer, Monday, 2017, 01.00:01.15, North, OFF

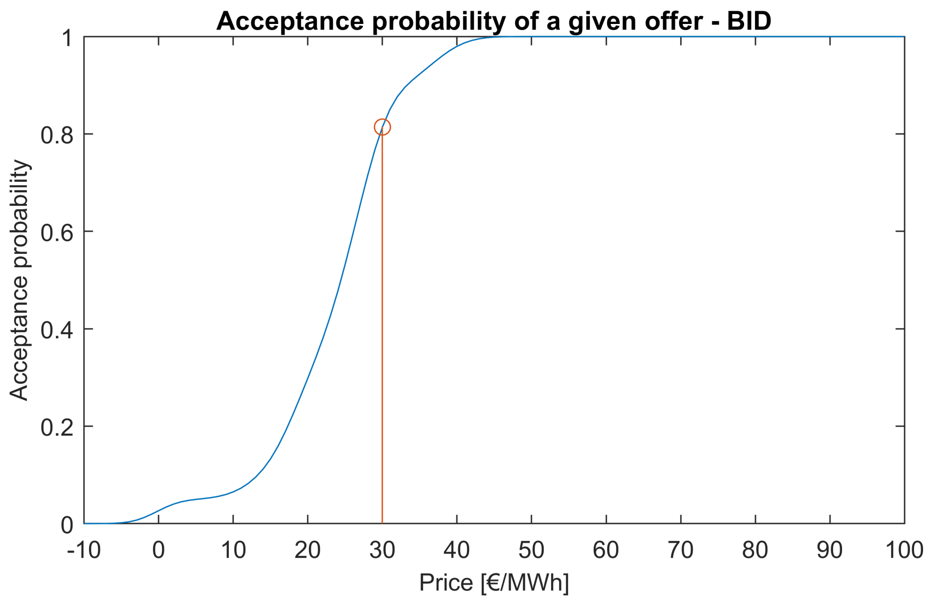

Figure 4.8: Acceptance p.f of a bid, Monday, 2017, 01.00:01.15, North, BID

These results are relevant for the quarter of hour 01.00:01.15 of Monday day of the representative week for year 2017; as observable the acceptance probability is almost of 80% in both of the considered cases.

4.2.2 Results and considerations

According to the adopted data organization many graphs and results are available; the most representative are shown in the following paragraphs in order to provide a good overview of the tool potentialities. Plots are organized according to representative weeks, differentiated by reference period, namely: year, month or season. For each of these main distinctions, comparisons between different market zones, different purposes and scopes will be presented.

4.2.2.1 Yearly aggregation

In this paragraph the yearly representative week will be considered. Several plots will be depicted in order to provide an overview of the obtainable data from this tool, focusing the considerations on 4 market zones, namely: North, North-Centre, South-Centre, South. In Figure 4.9 and Figure 4.10 the yearly average profiles of a day and of week are presented respectively; both of them refer to the OFF offers in the North zone, year 2017 and GR1.

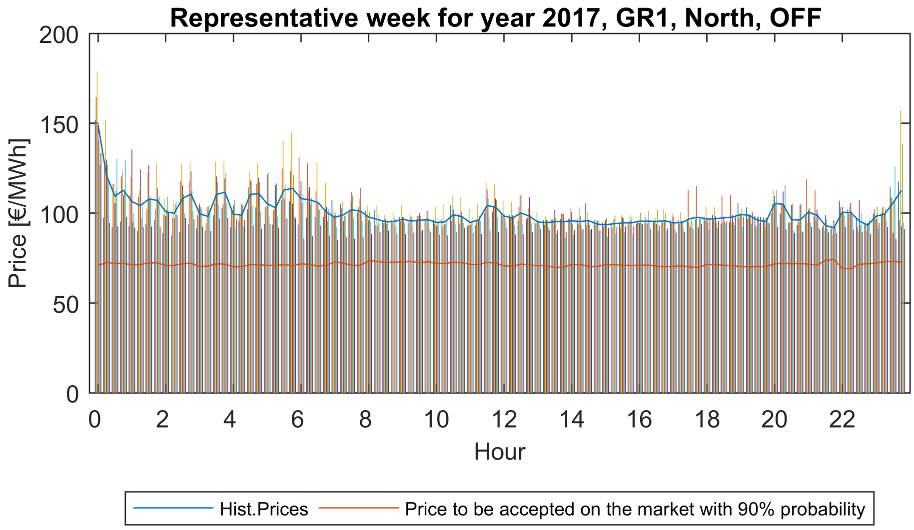

Figure 4.9: MB prices relative to the average day, 2017, GR1, North, OFF.

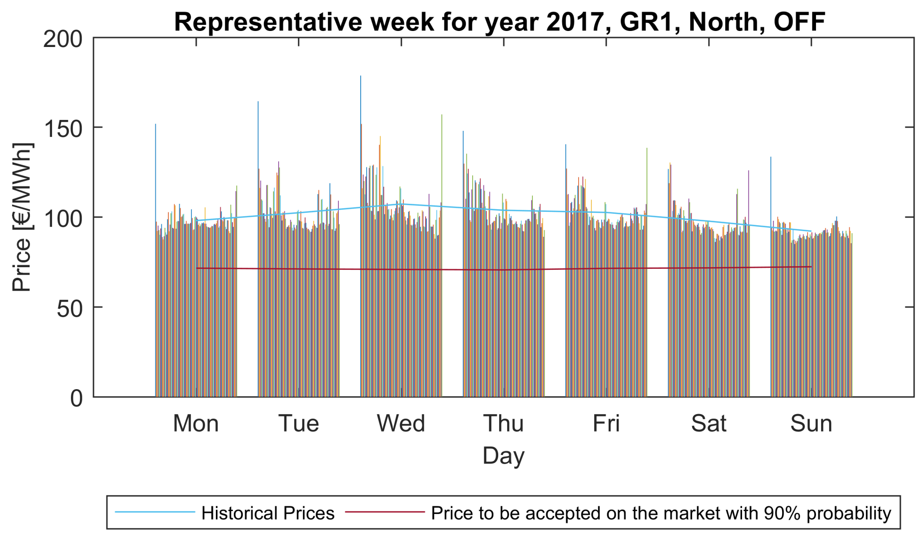

Figure 4.10: MB prices relative to the average week, 2017, GR1, North, OFF.

It is possible to distinguish between the historical average price and the average price to submit in an offer in order to have an acceptance probability of 90%. These values are represented by the blue and red curves which are defined for each quarter of hour. Reporting the same data also for GR4, it is possible to obtain Figure 4.11 and Figure 4.12. It is easy to realize how, with respect to GR1, the accepted offers are lower and have higher value; this agrees with the offer structure introduced in the initial chapters.

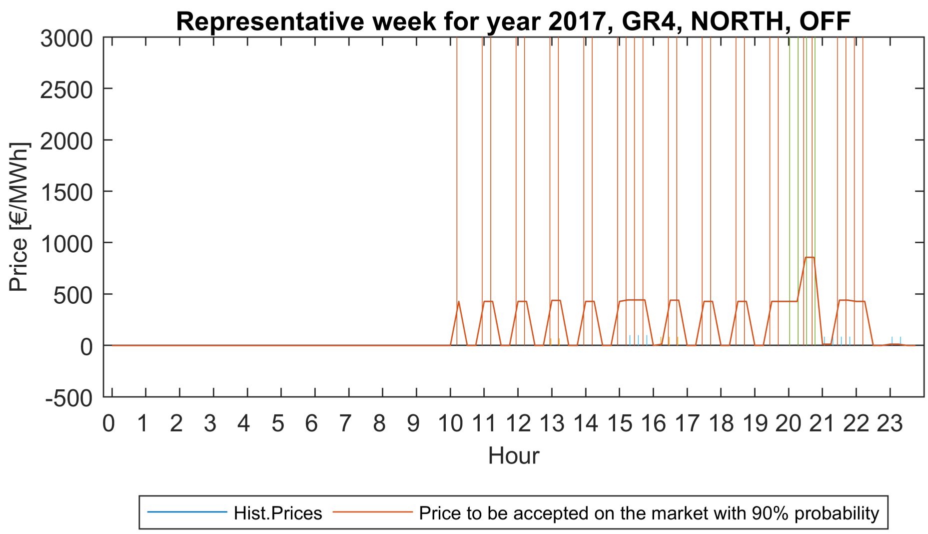

Figure 4.11: MB prices relative to the average day, 2017, GR4, North, OFF.

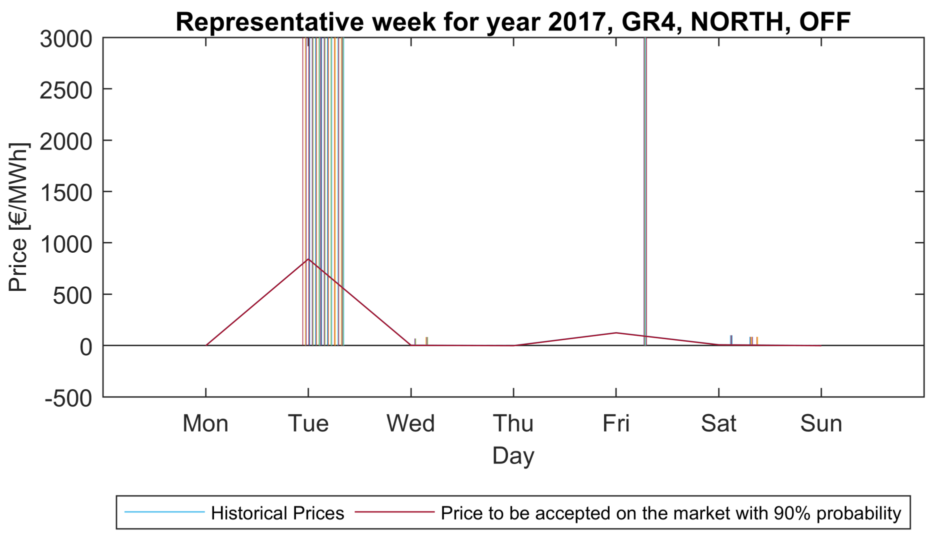

Figure 4.12: MB prices relative to the average day, 2017, GR4, North, OFF.

In the previous graphs, additionally to the price curves, also many colored bars were reported; a zoom-in of Figure 4.9 and Figure 4.10 is reported in Figure 4.13 and Figure 4.14.

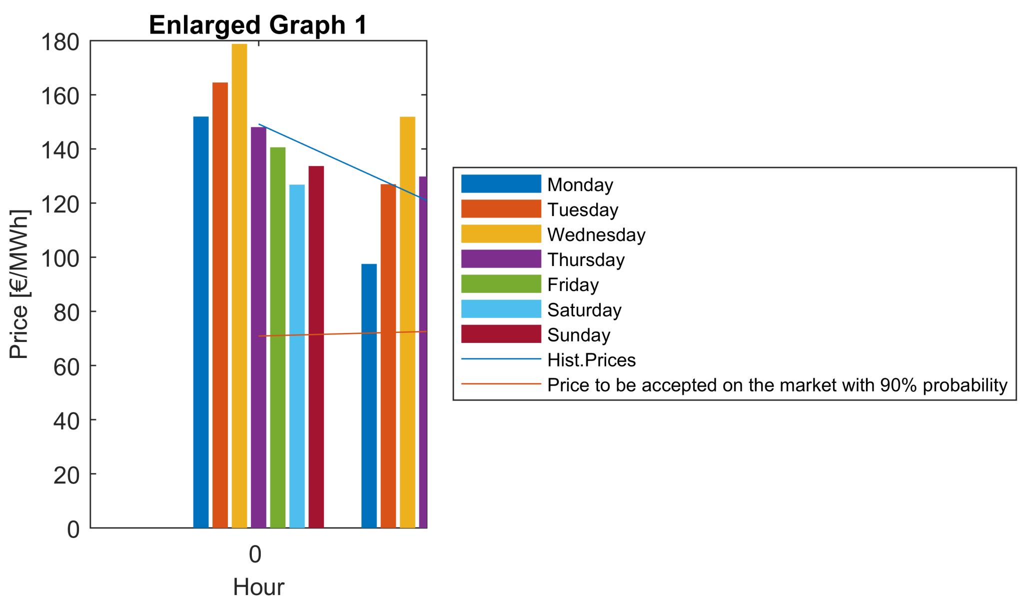

Figure 4.13: Zoom-in of average day, 2017, GR1, North, OFF.

In this case, each bar is representative of a week day; in particular, each bar reports the average value of the specified quarter of hour of the specified day. The blue and red curves, instead, are the average value of all the bars so they account for the average value of the price in a specific quarter of hour.

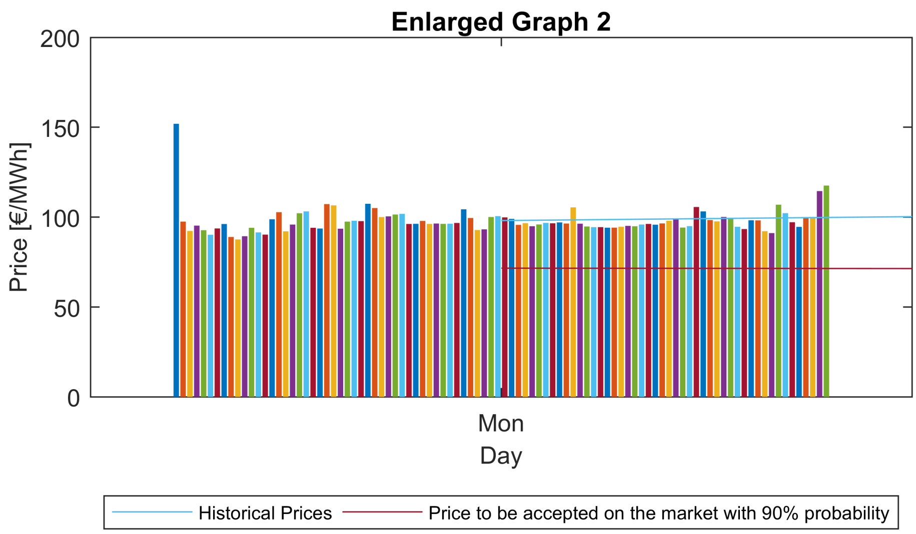

Figure 4.14: Zoom-in of average week, 2017, GR1, North, OFF.

Similarly, in this case, each bar represents a specific quarter of hour of the specified day, so the blue and red curves are the average of the value of these bars and indicate the average price registered in the specified day. However, since their value is not appreciable in these graphical representation, from now on these bars will not be reported. As already outlined, the scope of the offer is not a relevant distinction for this work purposes. Therefore, from now on, the presented results have been obtained considering all the accepted offers without grouping them by offer scope. A comparison can be done considering Figures 4.15, 4.16, 4.17, 4.18, 4.21, 4.22, 4.19, 4.20, 4.23 in which the prices relative to different market zones are reported for OFF offers.

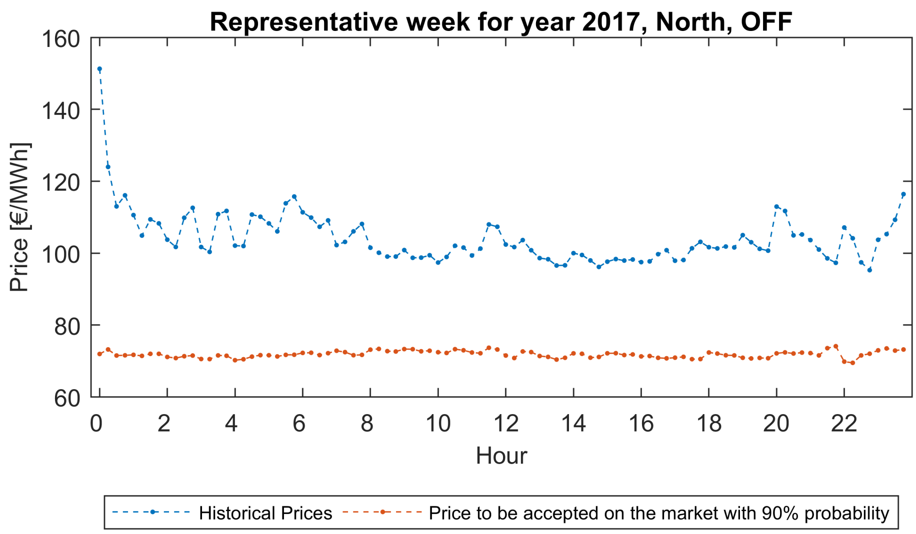

Figure 4.15: MB prices relative to the average day, 2017, North, OFF.

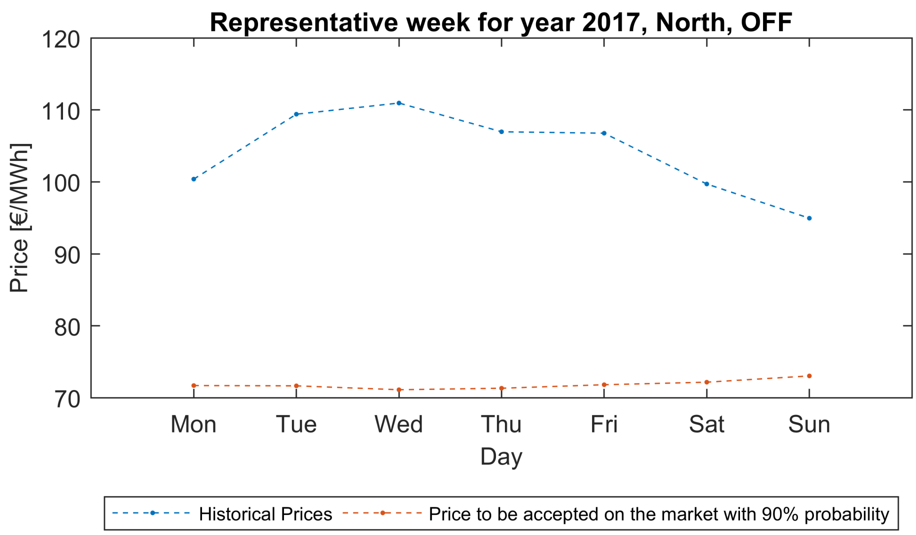

Figure 4.16: MB prices relative to the average week, 2017, North, OFF.

In the North of Italy, the historical average price almost varies in a range from 90 €/MWh to 120 €/MWh. Moreover, it is possible to observe how the higher prices have been registered in the night hours while during the day they result lower and follow a more constant trend; the price to be offered in order to be accepted with the 90% of probability is almost constant and approximately equal to 70 €/MWh. Finally, it can be noticed that the highest prices have been registered on Wednesday and that holidays registered lower prices with respect to weekdays ones.

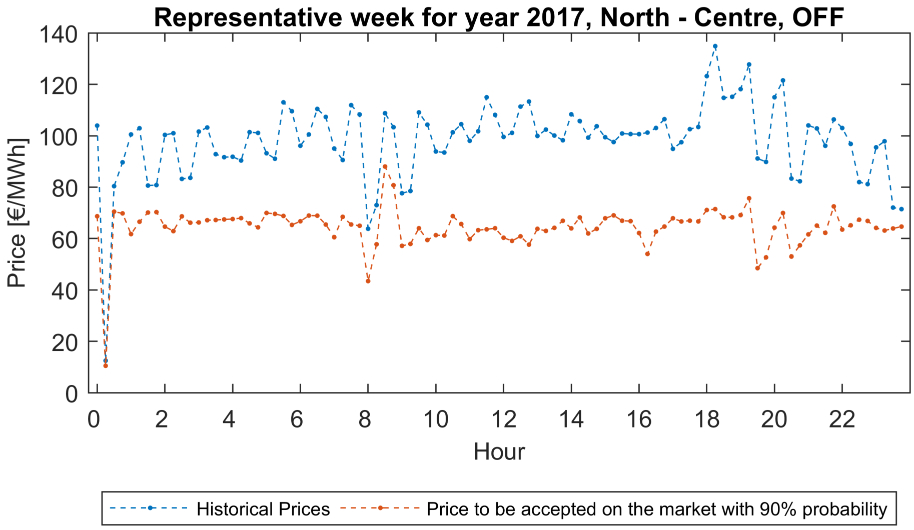

Figure 4.17: MB prices relative to the average day, 2017, North-Centre, OFF.

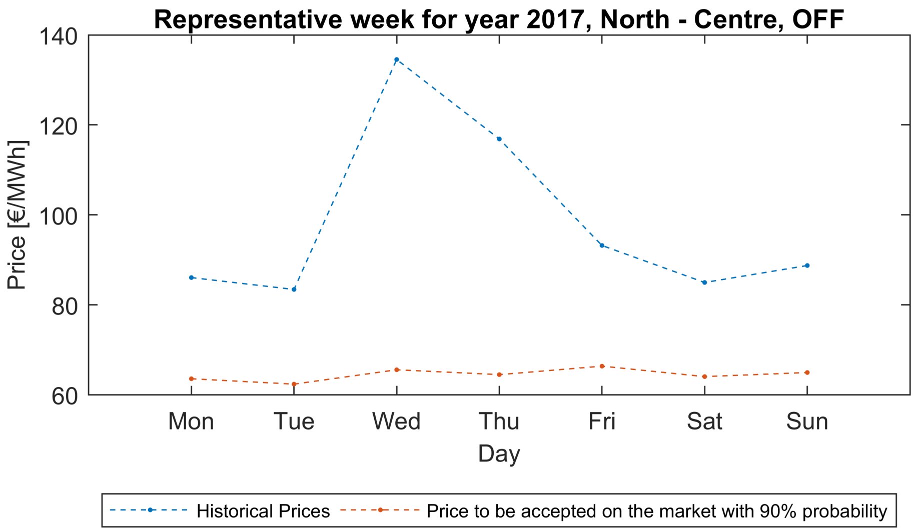

Figure 4.18: MB prices relative to the average week, 2017, North-Centre, OFF.

North-Centre zone reports a behaviour similar to the one of the North zone, with the higher prices still registered on Wednesdays during the evening hours. The price to be offered in order to reach 90% acceptance probability is a little bit lower with respect to North region. The decreasing trend from weekdays to holidays prices is confirmed also in this case as it was for North market zone.

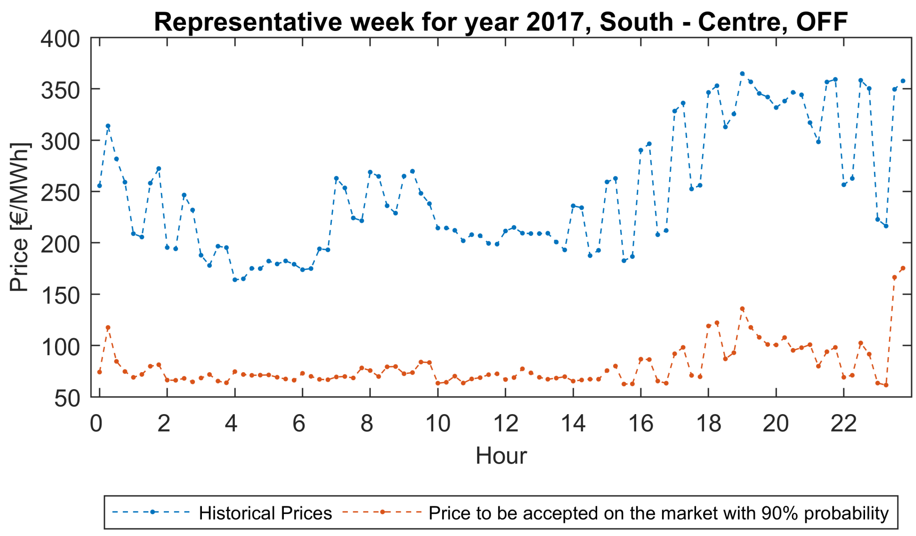

Figure 4.19: MB prices relative to the average day, 2017, South-Centre, OFF.

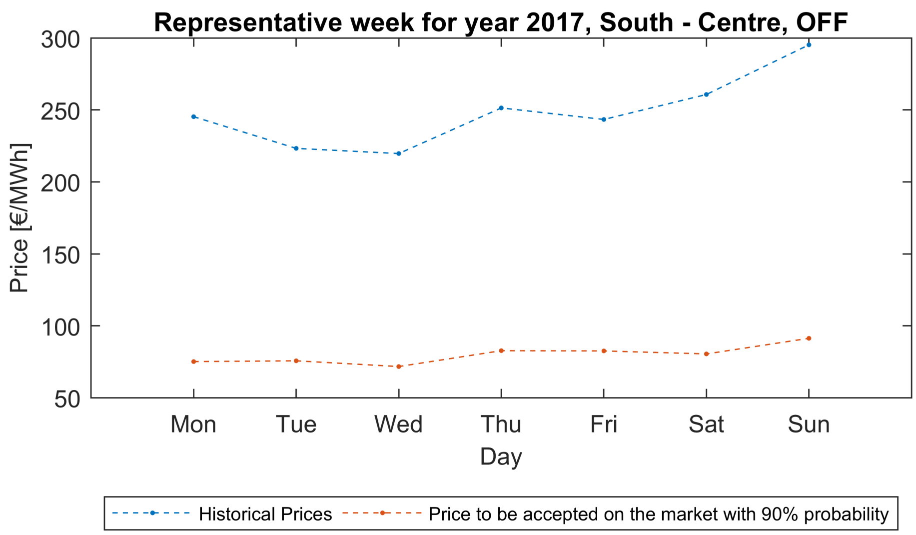

Figure 4.20: MB prices relative to the average week, 2017, South-Centre, OFF.

With reference to the South-Centre market zone a different behaviour with respect to the Northern areas can be pointed out. The historical accepted offers result much higher, showing an increasing trend during evening and night hours of the day; particularly, Sunday reflects the higher market prices. For what concerns the prices to be offered in order to be accepted with a certain probability, they are higher if considered hourly but, on a daily average, on a day, they result almost equal to the ones of the Northern zones. Oppositely to what observed in the previous cases, the holidays are characterized by higher prices with respect to weekdays.

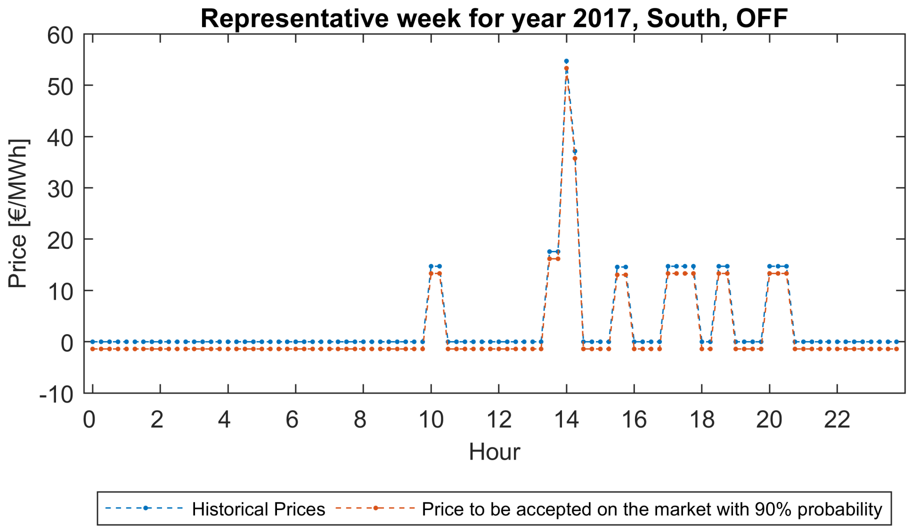

Figure 4.21: MB prices relative to the average day, 2017, South, OFF.

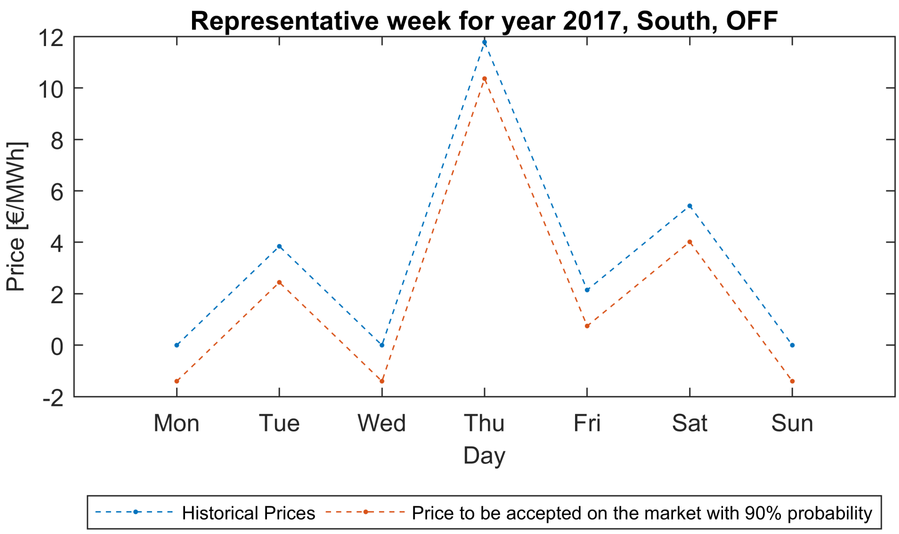

Figure 4.22: MB prices relative to the average week, 2017, South, OFF.

Finally, focusing our attention on the South market zone, it is possible to realize that practically only null price offers have been made; in fact, just a few that differ from zero are observable from 10 a.m to 21 p.m. This is reflected on the 90% probability acceptance price that results negative for certain periods, due to the statistical analyses that have been carried out. In fact, these values suggest that in order to be accepted, it would be necessary to pay Terna in order to be allowed to inject power into the grid; from an economical point of view this would not make any sense.

For what concerns the BID offers, instead, the results are reported in Figures 4.23, 4.24, 4.25, 4.26, 4.29, 4.30, 4.27, 4.28.

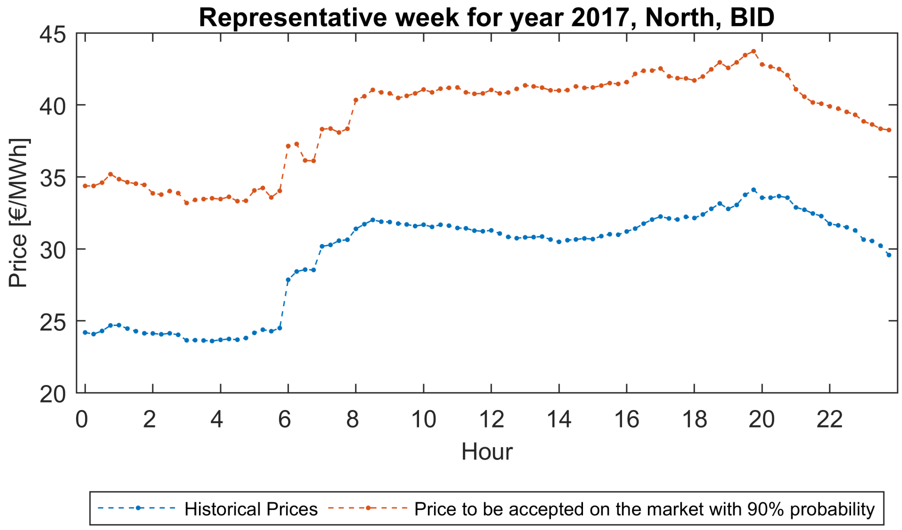

Figure 4.23: MB prices relative to the average day, 2017, North, BID.

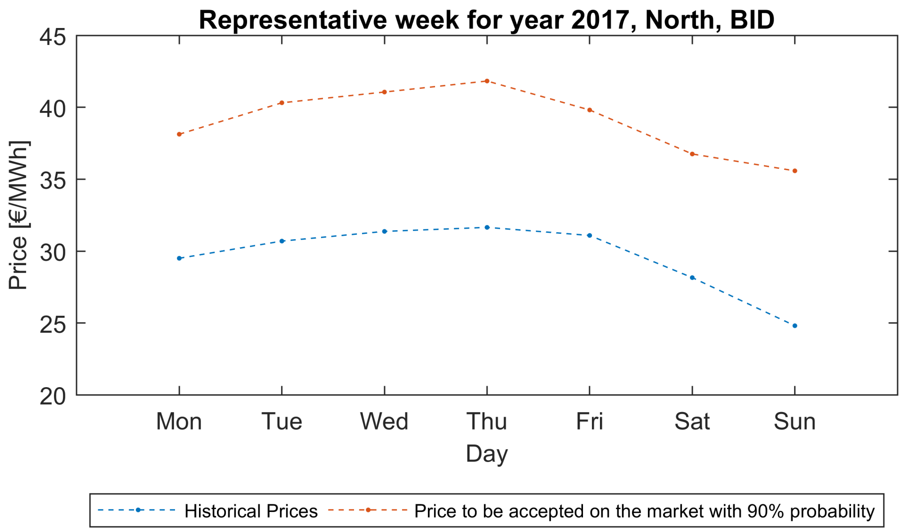

Figure 4.24: MB prices relative to the average week, 2017, North, BID.

North market zone is characterized by BID offer prices with an increasing trend in the morning hours from 4 a.m to 9 a.m, which later becomes quite constant with a price varying around 30 €/MWh. Grouping the offers to retrieve a representative week, it is easy to realize that holidays are characterized by lower values with respect to weekly days.

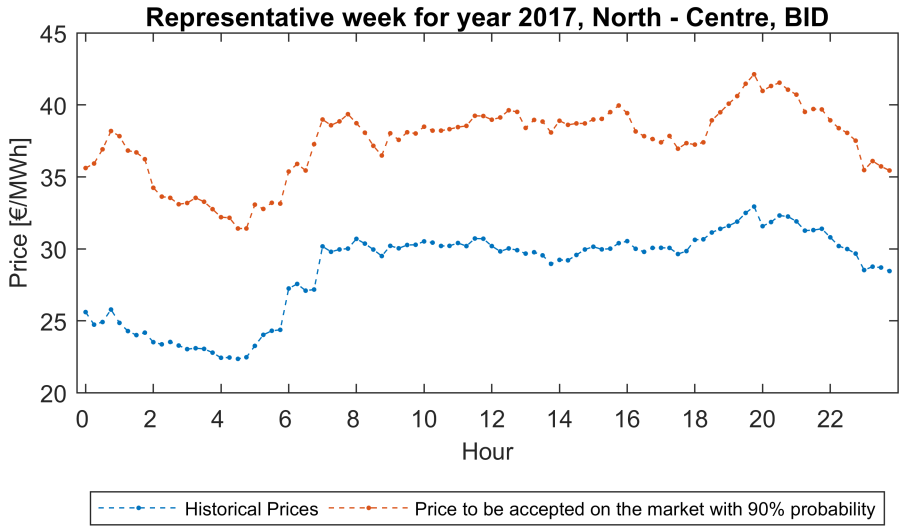

Figure 4.25: MB prices relative to the average day, 2017, North-Centre, BID.

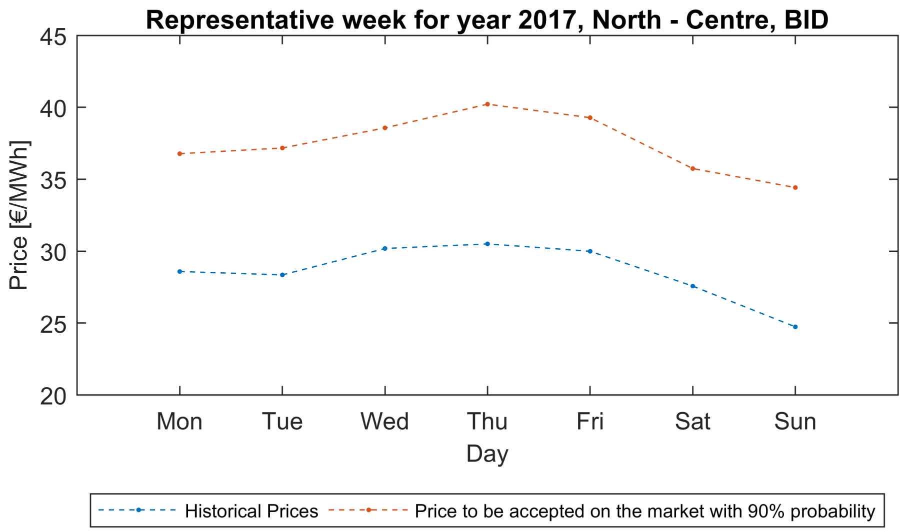

Figure 4.26: MB prices relative to the average day, 2017, North-Centre, BID.

Concerning North-Centre of Italy, the same considerations discussed for the North zone hold; only a low decreasing in prices can be observed, compared to the previous zone.

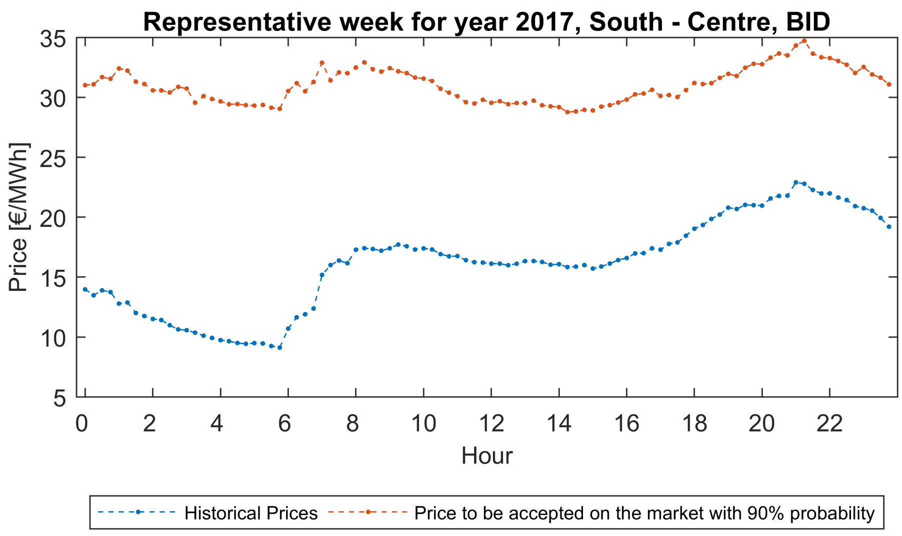

Figure 4.27: MB prices relative to the average day, 2017, South-Centre, BID.

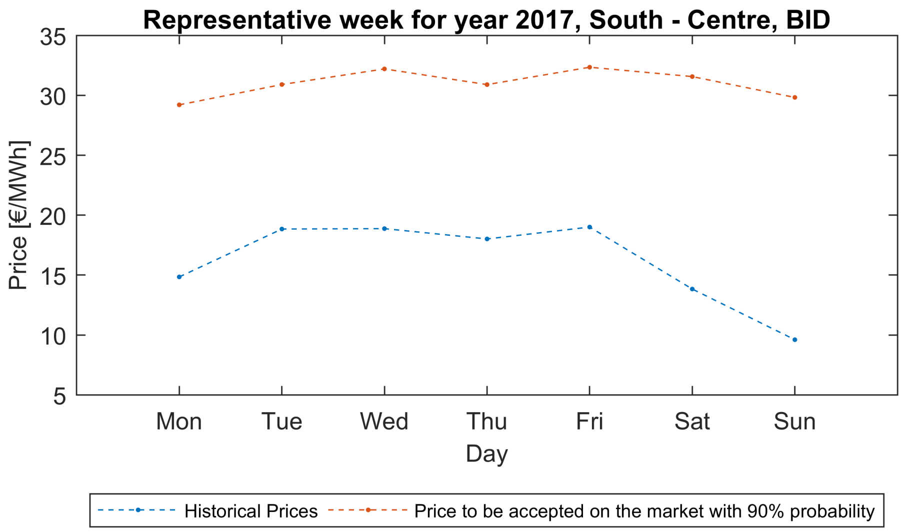

Figure 4.28: MB prices relative to the average day, South-Centre, BID.

The decreasing offers for South-Centre market zone present lower values with respect to the Northern ones. Anyway, an increasing price ramp in the morning hours and a lowering of the prices in the holidays with respect to weekly days can be noticed.

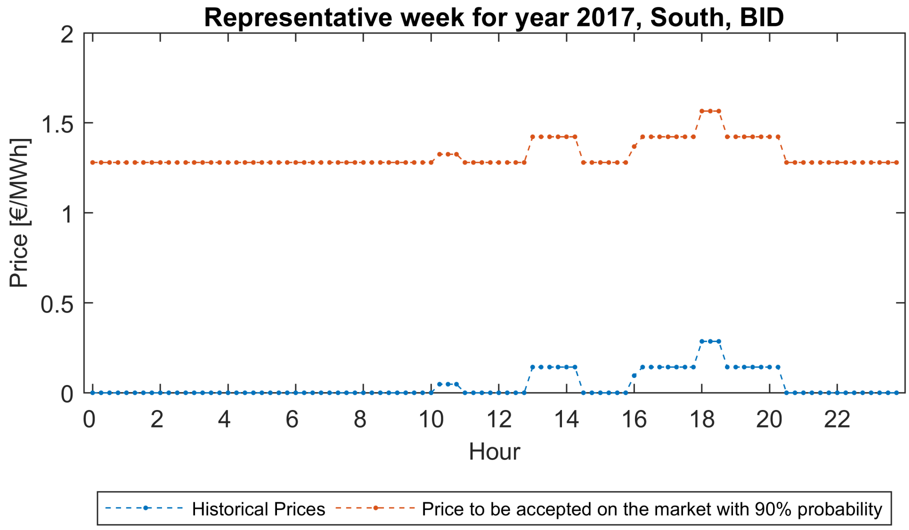

Figure 4.29: MB prices relative to the average day, 2017, South, BID.

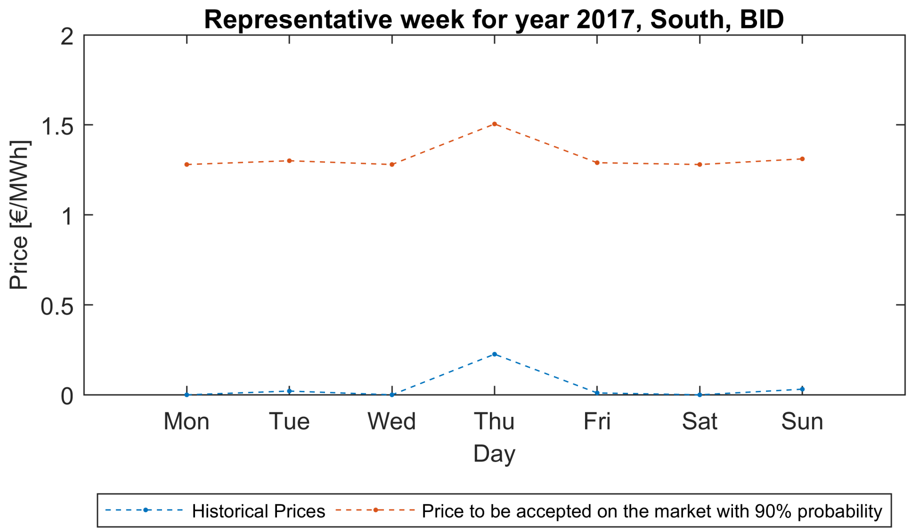

Figure 4.30: MB prices relative to the average day, 2017, South, BID.

Finally, South market zone is represented by low price offers, almost all of them equal to 0 €/MWh.

In this case, it is necessary to remark that the price to be offered does not always present the same trend of the historical prices, as it can be observed both in OFF and BID offers. This is related to the different weight given to the accepted offers; if we consider a set of 40 accepted offers presented in a given quarter of hour, and 5 of these offers present a very high value with respect to other 35, the average value is affected by these 5 offers even if they are just a minority. On the opposite, when the acceptance probability is evaluated, these 5 offers have quite a negligible effect with respect to the others 35 thanks to the KDE estimation. For this reason, the historical price curve is not constantly followed by the 90% acceptance probability price curve. As a general rule it can be stated that the more the offers are the less the two prices curves will follow each other and viceversa, because they have less impact since they are considered outliers on the KDE.

4.2.2.2 Seasonally aggregation

Since in Chapter 5 the analyzed aggregate will be hypothetically installed in the Northern part of Italy, for seasonal data aggregation only the North market zone will be analyzed. In the next, seasonal comparison is depicted.

In Figures 4.31 and 4.32 the daily and weekly seasonal comparison are carried out.

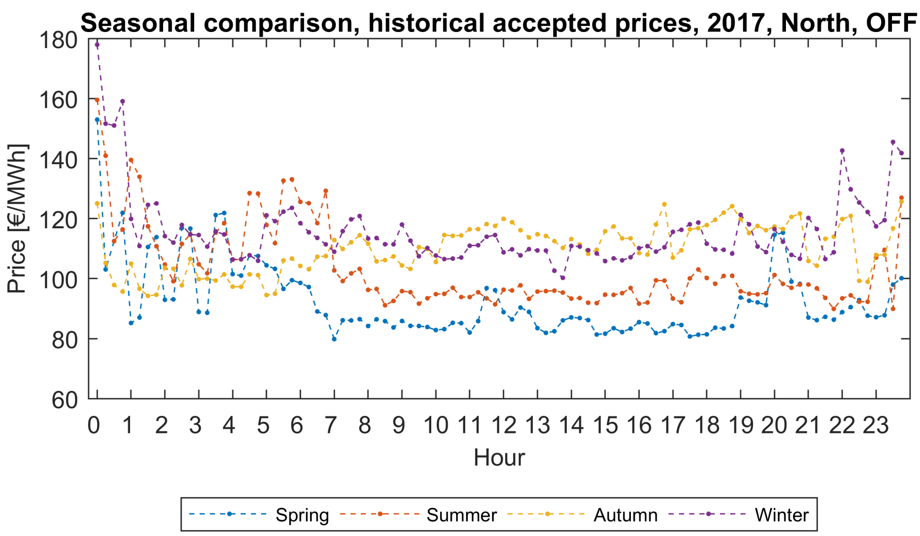

Figure 4.31: Seasonal daily comparison, 2017, North, OFF.

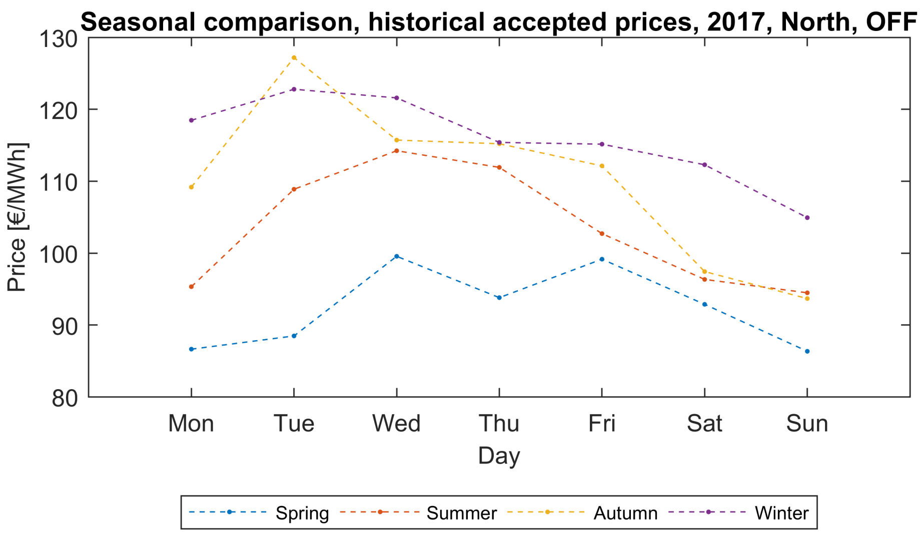

Figure 4.32: Seasonal weekly comparison, 2017, North, OFF.

It can be observed that morning and night price gradients are a common characteristic for all seasons, assuming particularly high values for autumn and winter. Moreover, looking at the weekly comparison, it is possible to observe a general decreasing of prices in the holidays with respect to the weekdays.

For what concerns BID offers, in Figure 4.33 and 4.34 seasonal daily and weekly comparisons are depicted.

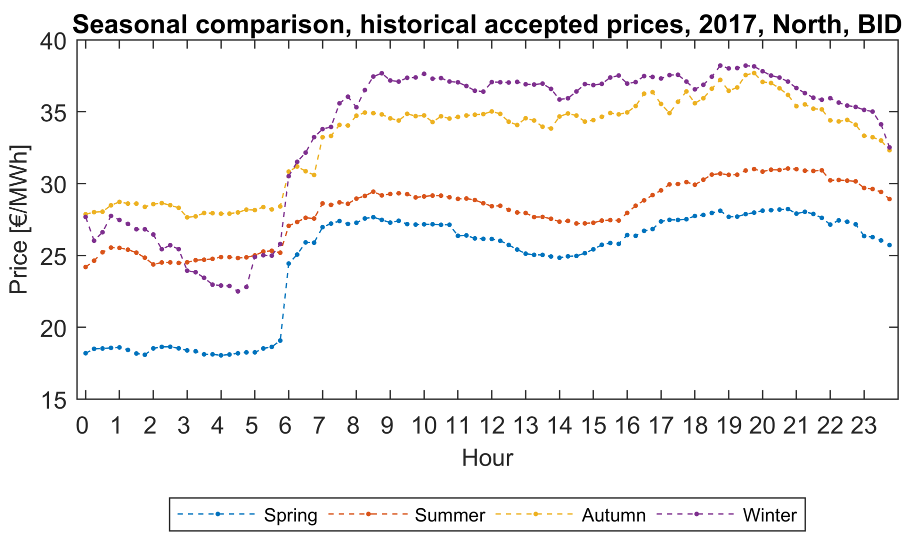

Figure 4.33: Seasonal daily comparison, 2017, North, BID.

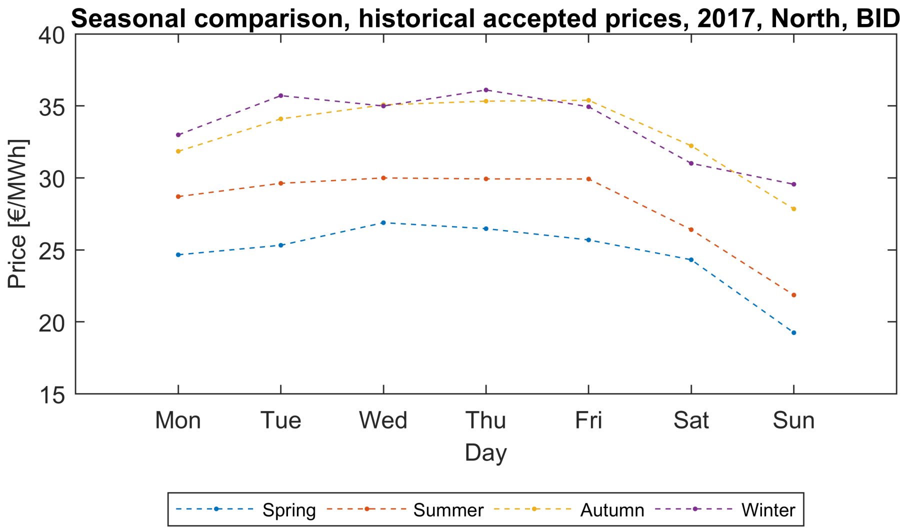

Figure 4.34: Seasonal weekly comparison, 2017, North, BID.

As for the previously analyzed graphs, winter and autumn are clearly characterized by higher prices compared to other seasons. All the curves present an high gradient in morning hours and, comparing weekly behaviour, it results that holiday prices are lower with respect to weekly ones.

4.2.2.3 Monthly aggregation

The motivation pointed out for seasonal aggregation led to the choice of presenting the monthly data only for North market zone. Daily and weekly behaviours are depicted in Figure 4.35 and Figure4.36 for OFF offers.

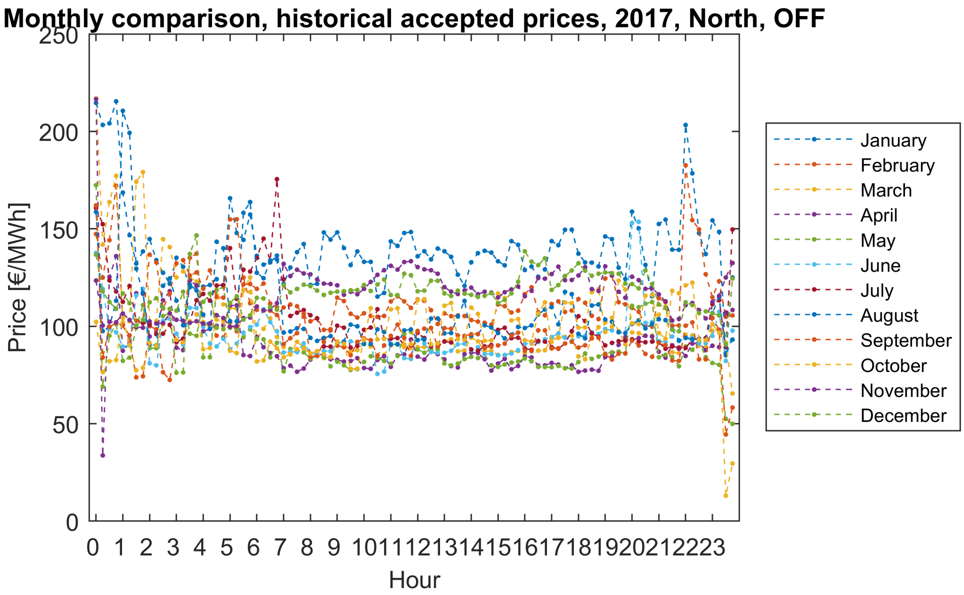

Figure 4.35: Monthly daily comparison, 2017, North, OFF.

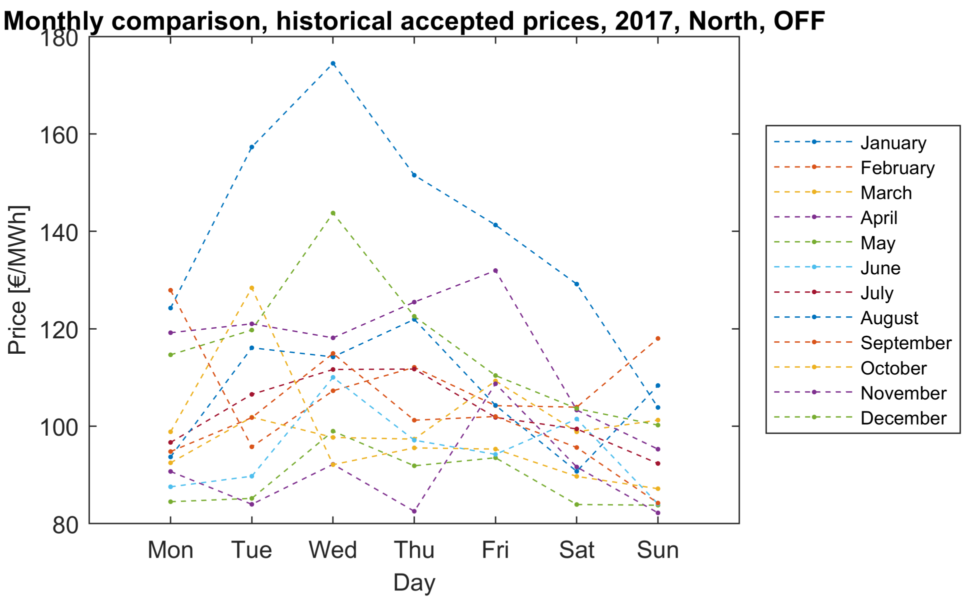

Figure 4.36: Monthly weekly comparison, 2017, North, OFF.

Due to the high number of data represented in daily comparison, the relative graphs present a very low readability however, the information that can be pointed out is that colder months are clearly shown higher prices with respect to the others.

Same information can be retrieved from the weekly comparison, confirming the trend of holidays to presenting lower prices with respect to weekdays.

Same representations are reported for BID offers in Figure 4.37 and Figure 4.38.

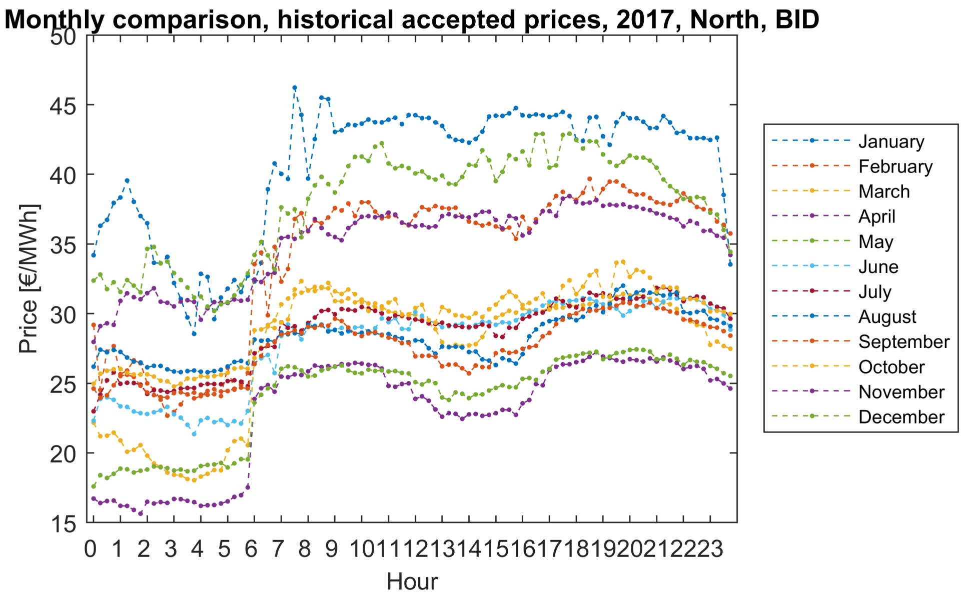

Figure 4.37: Monthly daily comparison, 2017, North, BID.

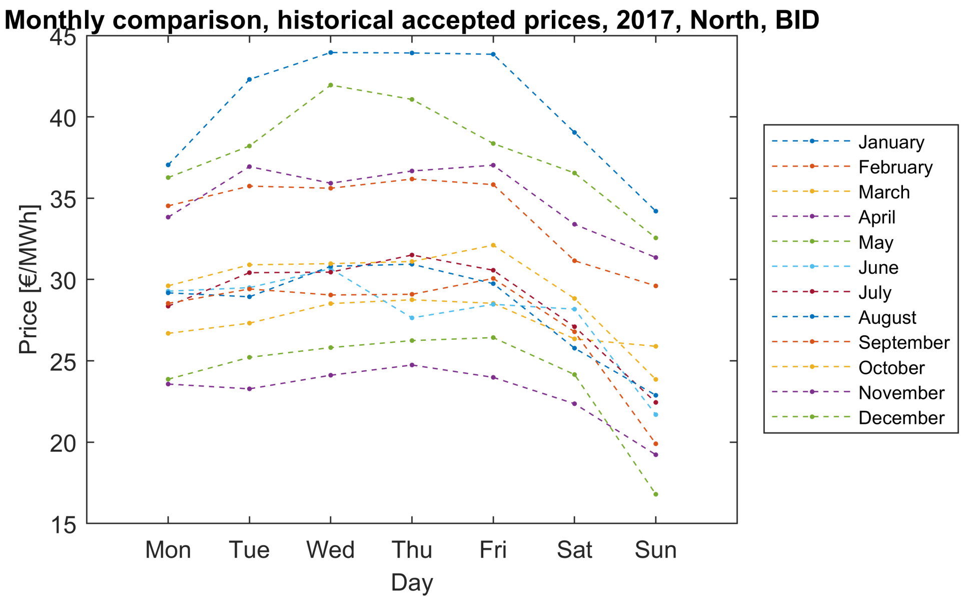

Figure 4.38: Monthly weekly comparison, 2017, North, BID.

November, December and January confirm to have the higher prices also for BID offers; all curves present an high gradient in morning hours. As observed in previous graphs, it is possible to retrieve that holidays present lower prices with respect to weekdays and that November, December, January and February registered the higher prices in the MB market.

4.2.2.4 Detailed evaluation

The developed tool also allows to analyze specifically a given quarter of hour in order to retrieve information about the market behavior in that period. Some demonstrative examples are reported in the following. In detail, in Figure 4.39 it is possible to observe the behaviour of the market, evaluated considering the representative week for December 2017. Precisely, the analysis illustrates the day of Thursday, from 2.00 pm to 3.00 pm, for North market zone, GR1 and for increasing offer.

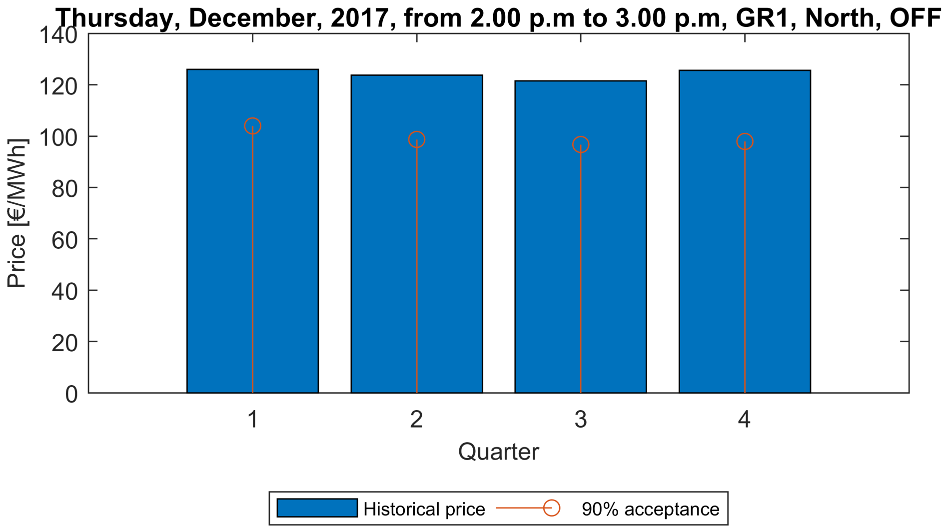

Figure 4.39: Thursday, December, 2017, 2.00 pm:3.00 pm, GR1, North, OFF.

Blue bars represent the historical price registered in that period, while the red circled lines represent the price that has to be offered in order to be accepted in the market with 90% of probability. The same is obtainable, for example, studying the same period but focusing the attention on decreasing offers, as observable in Figure 4.40.

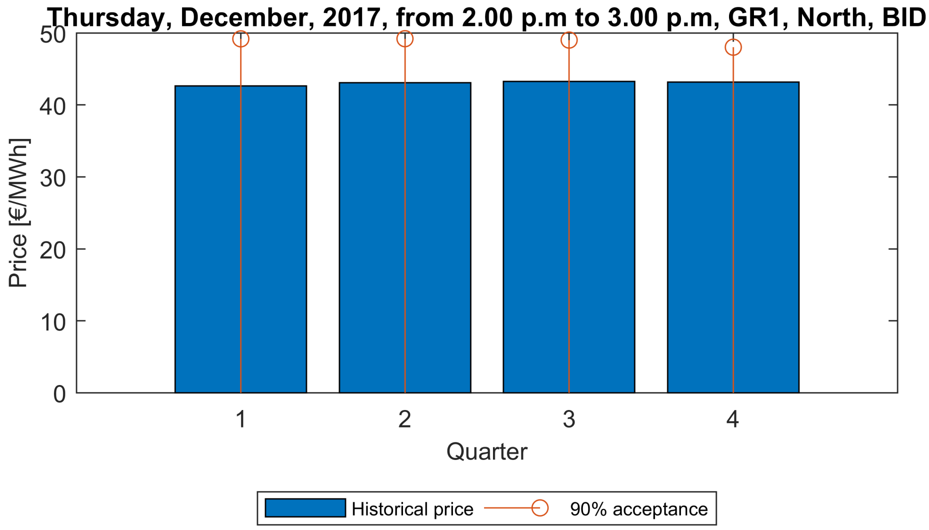

Figure 4.40: Thursday, December, 2017, 2.00 pm:3.00 pm, GR1, North, BID.

As introduced, in this chapter an overview of the *market analysis tool* has been provided, reporting the graphs and examples for an acceptance probability of 90%, this parameter can clearly be changed accordingly to user preferences. In chapter 5 results obtained with this tool have been exploited in order to provide the optimizer with a vector of prices to be used in the objective function as it will be further discussed.

Chapter 5

Optimizer for VPP balancing market participation

This last chapter wants to be a summary of all the concepts previously pointed out in this final dissertation. Compared to the Italian situation concerning *demand response*, which is still in a trial phase with respect to other places in the world, a step forward has been implemented. Particularly, an hypothetical UVAM, sited in the North of Italy, has been considered along with its optimal bidding strategy in the balancing market in order to provide increasing power services, as better explained in the next section. The simulation has been carried out with MATLAB software, adopting yalmip toolbox [18] for the formulation of the optimization problem; the adopted solver is CPLEX. With the goal of giving a general idea of the simulated optimization processes, in the next section an informal problem description is presented.

5.1 An easy-understandable problem formulation

In this section, an informal description of the hypothetical simulated scenarios is presented, while the formal and mathematical formulation is reported in the next one. The base idea is to analyze which could be the potentialities of deep *demand response* integration in the actual Italian scenario; in this work the key role is covered by the *prosumer*, that is enabled to supply a very high flexibility level to the aggregator for MB market participation. The main idea is to let the user covering an active role in the market, without making him loose the comfort of the passive user. This means that the routine of the user has not to be modified or, more realistic, it has to be modified as less as possible; moreover, every behavior that would somehow lead to a lack of comfort for the user has to be economically remunerated.

From a practical point of view, some of the users belonging to the aggregate install smart-devices, and allow them to be remotely controlled by the aggregator according to their preferences. The considered users are residential and commercial ones, the former are characterized by a set of smart-devices constituted by a washing-machine (WM), a dish-washer (DW) and an air-conditioning system (AC); the latter allows only air-conditioning system to be remotely controlled. Of course, it is not mandatory for a unit to install and/or to let a smart-device to be controlled by the aggregator. This depends on the user preferences that can vary day-by-day or even many times during the same day. Regarding the air-conditioning system a modulation of its absorption profile is considered as the provided flexibility; this variation has been computed with respect to a reference profile absorbing an average power for a certain time. With respect to this cycle, an elapse variation and a power modulation are allowed, keeping that the total absorbed energy equals the reference cycle one. This is possible exploiting the thermal inertia of the units. On the other hand, dish-washers and washing-machines allow their operation cycle to be shifted during the day. The assumption that justifies this choice is that a user is more interested to have DW and WM cycles ended within a certain time than to have them started at specific time. To clarify this, imagine that a worker starts the WM cycle in the morning, before going to work, so to have it done by the end of the day when he comes back. Obviously, the user is interested to have the cycle done once he comes home and not to have it started before going to work. The flexibility provided by these loads is therefore to allow the cycle to start at different times, which would not change significantly the user effort, since instead of pushing the start button in the smart-device he would push an hypothetical *available button* that notifies the aggregator that the device is available for being controlled. A control system is needed in every unit but, nowadays, this is not a huge problem since a small laptop or a small bounded computer would be enough to mange a single unit. Near to residential units, also commercial ones are considered; they allow only the air conditioning control, adopting the same logic introduced for residential units. Each unit could also install PV plants and/or ESS that, as for smart devices, can be managed by the aggregator for market purposes. For a unit, the main advantage to be part of an aggregate is the economic remuneration which can obtain from the aggregator that, thanks to the users flexibility, can participate to the ancillary services market and generate incomes.

The optimization problem can be structured in two main parts:

1. First part is just a preliminary one necessary to obtain the *reference profiles*, these are representative of the behavior of a unit, as no smart devices but ESS were present. This means that cycles are started when users decide to start them, without allowing any load shifting or curtailment; the optimization only accounts for the possible installation of an ESS and its optimal working cycle. Each unit is optimized by its own and no interactions between different units occur. In other words, an historical profile has been retrieved to characterize

each unit, which could have been alternatively done by monitoring the consumption, load by load, of many different units in the northern of Italy, which is clearly unfeasible for the purposes of a master thesis from an economical point of view;

2. Second part is the most important, as in this case also a new agent is introduced in the problem structure, namely the aggregator; its role consists in receiving the references profiles from every unit, evaluating the available flexibility, and forwarding back different set points for the controllable devices so to achieve a defined goal, that is different for the two considered scenarios.
    - In the first approach, the aggregator, according to acceptance probability prices computed in the previous chapter, finds out the time interval and the power variation that would lead to the most profitable MB participation; it forwards to the grid operator the required baseline and the variation that it can realize with respect to it. It is important to highlight that, in this scenario, the operator does not know for sure if it will or not be accepted by the market, just knowing which is its probability;
    - In the second approach, the aggregator is sure to be accepted by the balancing market in a specified time interval and for a specific power quantity; therefore, the optimization algorithm has not to find out which is the best time interval and the best quantity to submit in the offer to be accepted by the market with a certain probability. The only goal is to minimize the operational costs of the aggregate in order to achieve the defined variation in the specified time interval. Is it clear that this approach requires a very low computational time effort with respect to the previous scenario.

5.2 UVAM constitution

The aggregate is constituted by residential units, commercial units, renewable generation and storage systems.

3000 residential units are considered, disregarding the fixed load, each unit is allowed to install the following flexible devices:

1. solar generation: characterized by a nominal power of $P_{solar_n} = 4kW$;
2. storage system: characterized by a nominal power $P_{ess_n} = 3\,kW$ and a nominal energy $E_{ess_n} = 10\,kWh$;
3. controllable dish-washer (*load shifting)*: characterized by a cycle which elapses $t^{DW}_{cycle} = 2\,hours$ and on average absorbs almost $P^{DW}_{cycle} = 950\,W$. Each user can

decides the maximum end time, $t^{DW}_{end_{max}}$, of the cycle, which means that each user decides the time within the cycle must be ended;

4. controllable washing-machine (*load shifting)*: characterized by a cycle which elapses $t^{WM}_{cycle} = 1.5\,hours$ and on average absorbs almost $P^{WM}_{cycle} = 900\,W$. Each user can decides the maximum end time, $t^{WM}_{end_{max}}$, of the cycle, which means that each user decides the time within the cycle must be ended;

5. controllable air-conditioning *(load curtailment)*, which average cycle elapses $t^{AC}_{cycle} = 5\,hours$ and the average absorbed power equals $P^{AC}_{cycle} = 800\,W$; this cycle can be modulated increasing power absorption by a maximum power of $P_{max_{increase}} = 400\,W$ or decreasing it by a maximum power of $P_{max_{decrease}} = 400\,W$, additionally it can be started one hour and half earlier and/or ended one hour and half later with respect to the reference profile. Since the needed thermal energy cannot be modified, the amount of absorbed energy during the modulated cycle has to be equal to the one absorbed during the reference one.

A single commercial unit is considered, disregarding the fixed load, the unit is allowed to install:

1. solar generation, characterized by a nominal power equal to $P_{solar_n-c} = 500\,kW$;

2. controllable air-conditioning (*load curtailment)*, which is considered to be on all day long, absorbing a time varying power profile which is presented in the next; it can be controlled as illustrated for the residential case, the only difference is that power increase/decrease at time t ($P^{AC}_{max_{increase}-c}(t)$ /$P^{AC}_{max_{decrease}-c}(t)$) is defined as a percentage, 10%, with respect to the reference profile at time t.

It is important to point out that the listed devices are the allowed ones to be installed in a unit. However, a unit is not required to install them neither partially nor totally. Moreover, even if some of them are installed by a unit, it is not mandatory to make their flexibility available to the aggregator. This is important for the residential case in which it would not be realistic to consider 3000 units that allow the flexibility of all the listed devices. Finally, the air-conditioning system will be considered available only during summer period.

5.3 Reference profile definition

As mentioned in this chapter introduction, the goal of this algorithm is to obtain a reference profile to be used for the balancing market optimization. In the following all necessary data used in this process and how they have been obtained will be presented along with the mathematical constraints formulation.

5.3.1 Devices model

5.3.1.1 Residential

The adopted model is presented in Figure 5.1 for the i-user.

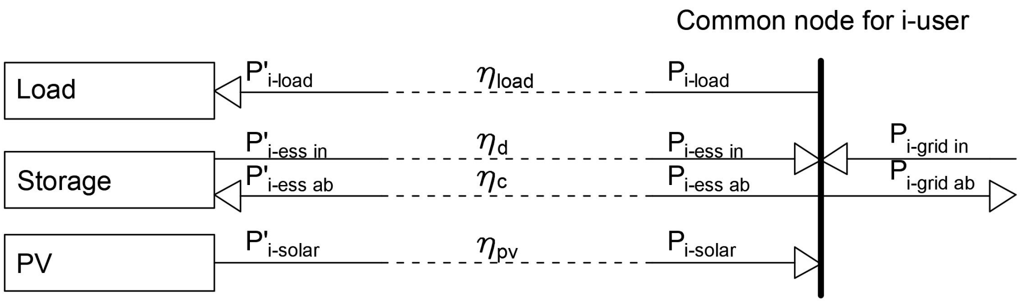

Figure 5.1: Residential unit model

Every device (load, storage, PV) is modeled with one or two variables depending on its capability of injecting and/or absorbing power. A common node is introduced in order identify the adopted conventions for the power balance. If an arrow is pointing the common node it means that power, positive, is injected into the grid; on the other end, if an arrow is pointing into the device it means that power, negative, is absorbed by the device. Electrical grid identifies the connection point of the unit with the public electrical system. Also the efficiency is modeled through a parameter identified by η, particularly, only for the storage system it has been chosen an η lower than one, both for charging and discharging operation.

A description of all the used devices is presented in the following, introducing the adopted mathematical constraints for the optimization algorithm.

Load For the evaluation of the reference profile no flexibility in the load has been considered. Particularly, two load profiles have been retrieved, one to be used during spring and summer, the other during autumn and winter. In order to obtain enough realistic results, the first step has been to look in the literature for already existing evaluations regarding absorption profiles of residential devices. A guideline has been found in the *Eureco project [19], Micene project* [20]and in *a CESI* report [21]. Particularly, these projects have been useful to identify the average hourly consumption of residential appliances, namely: illumination, freezer, bathroom-heater, iron, television, washing-machine, dish-washer and air conditioner; these average profiles have been obtained monitoring the consumption of a certain number of users and retrieving from the collected data an average profile that describes, in a day, which is the average consumption of the considered users for each considered appliance. Even if average profiles were available in the cited reports, a different approach has been adopted for dish-washers, washing machines and air-conditioners power absorption. The reason is that since these devices are responsible for load-shifting and load curtailment services, the average profile in a day is not useful. In fact it is important to define the exact time interval in which these devices are on, so that it is possible to define which is the time and the interval in which load-shifting and load curtailment can be applied. For these purposes the cycle power profile for these devices has been considered and from it the average value of absorbed power during a cycle has been retrieved. With these values it is possible to choose for each user and for each smart-device a starting time. From that time on, until the cycle is finished, the absorbed power of each device equals the average power of its cycle. In these way, summing the power absorption profiles of each device, the reference load profiles are obtained for each user. To clarify, these reference profiles will be constituted by the sum of the average power profiles of the non flexible devices (equal for every user) and the sum of the smart-devices profiles (different for each user); in Figure 5.2 and Figure 5.3 the summer reference absorption profile of two users are reported as an example. The red bars represent the absorption of washing-machine, dish-washer and air-conditioner while the blue bars are the power consumption related to the illumination, freezer, bathroom-heater, iron and television, assumed constant for every user.

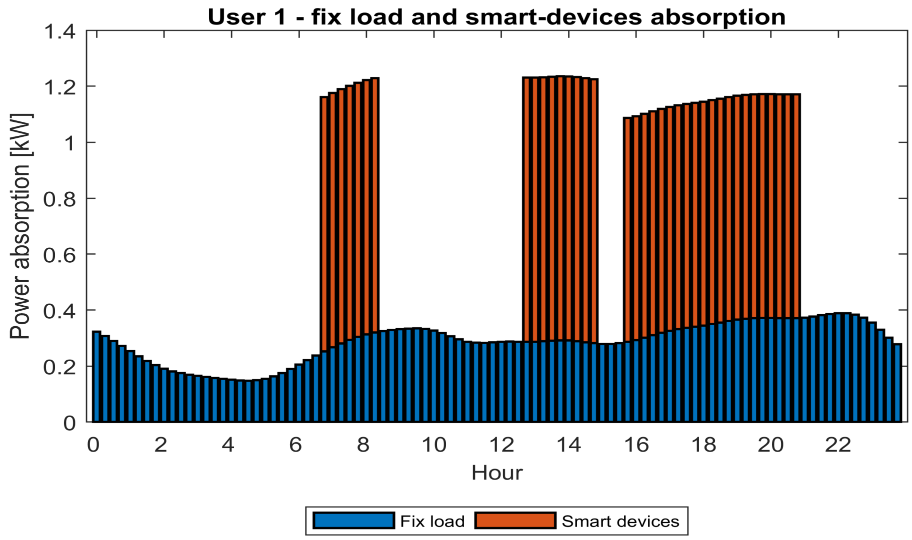

Figure 5.2: Fix load and smart devices absorption for user 1, summer

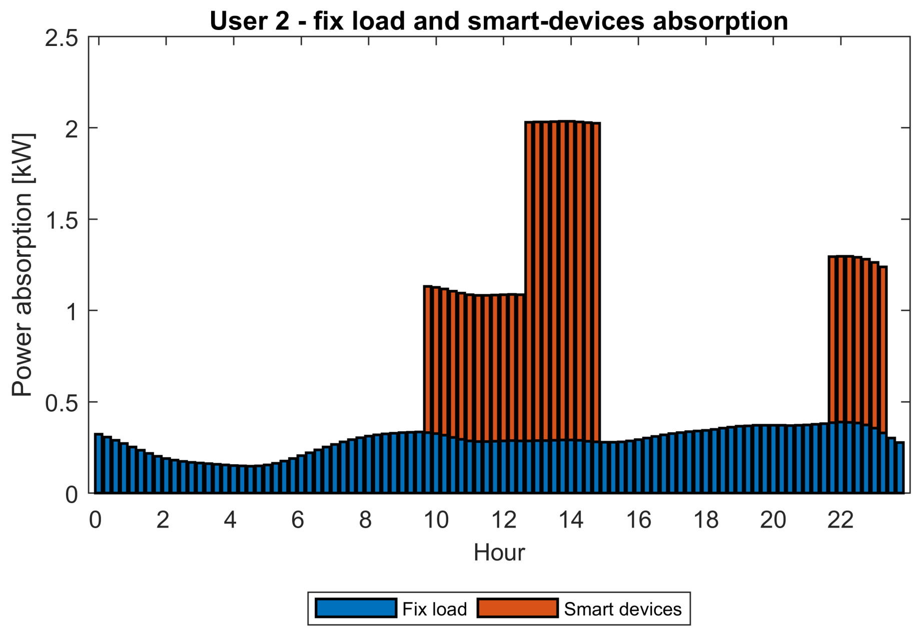

Figure 5.3: Fix load and smart devices absorption for user 2, summer

Regarding the mathematical formulation of the load, it is just identified by a constant value defined with a 15 minutes interval resolution for each i-user, namely.

$$P_{i-load}(k) \qquad for\ k = 1 : 96 \tag{5.1}$$

Solar Plant Residential units allow the installation of a solar power plant of small dimensions; the nominal power of the plant is of $P_{solar_n} = 4\,kW$. In order to retrieve the power output obtained by the solar power plant knowing its nominal power, the irradiance data of Codroipo, small town sited in Friuli Venezia Giulia, North-East of Italy, have been required to ARPA F.V.G. From these data, through an empirical formula [1] , the power profile supplied by the solar power plant has been obtained, it is represented in Figure 5.4.

[1]Relation between Irradiance (Irr) and Power (P) for a mono - crystalline silicon solar panel is linear and can be represented by: $P = 0.000898 \cdot Irr - 0.0138$; the considered tilt angle equals 36°.

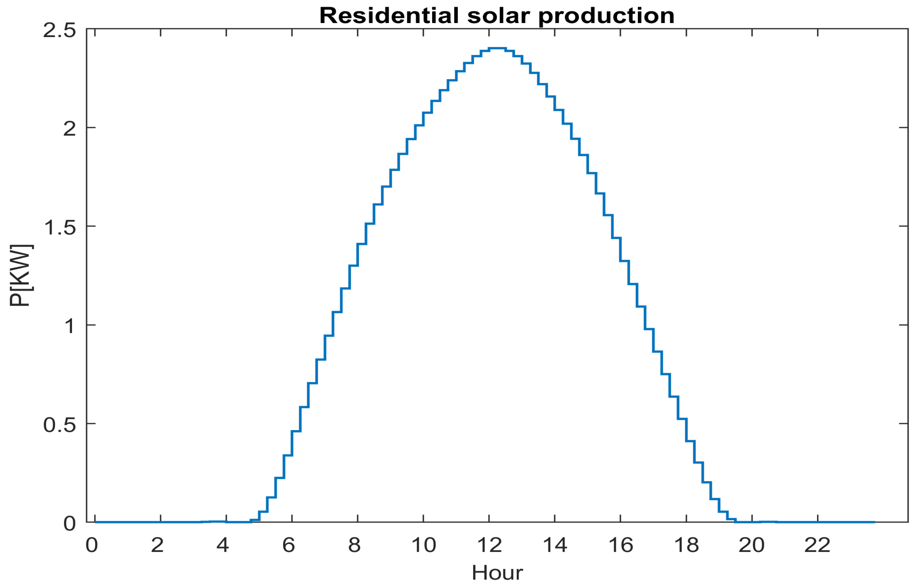

Figure 5.4: Residential solar production

The mathematical formulation is easy, and the output power of the solar power plant is represented by a constant value defined with a 15 minutes interval resolution for each i-user, namely:

$$P_{i-solar}(k) \qquad for\ k = 1:96 \tag{5.2}$$

Energy Storage System Coupled with the solar plant, some units could install a storage system, characterized by the following nominal values:

- $P_{ess_n} = 3\,kW$; $E_{ess_n} = 10\,kWh$; $RTE = 0.91$ that are the nominal power (P_{ess_n}) and the nominal energy (E_{ess_n}) of the ESS;
- $SoC_{min} = SoC_{start} = 0.1$; $SoC_{max} = 0.9$ that are the minimum (SoC_{min}), the starting (SoC_{start}) and the maximum (SoC_{max}) state of charge of the ESS;
- $lifetime = 10\,yers$; $lifecycles = 5000$ that are the lifetime and the maximum number of cycles of the ESS.

With respect to load and solar plant, energy storage system allows to absorb or inject power into the common node, for this reason, from a mathematical point of view, its formulation requires to adopt two variables, one referred to the injected power $P_{i-ess_{in}}$, the other referred to the absorbed one $P_{i-ess_{ab}}$ with reference to the common node. Moreover, in order to account for the energy storage efficiency, other two variables have to be introduced, namely: $P'_{i-ess_{in}}$ and $P'_{i-ess_{ab}}$ that respectively represent the injected and absorbed power at the battery terminals. Additionally, since the injection (discharging) and the absorption (charging) cannot occur at the same time, also a binary variable α_{i-ess} has to be defined in order to identify the charging and discharging operation mode, avoiding in this way their simultaneous occurrence. In Equations 5.3, 5.4 constraints limiting the injected and absorbed power within battery nominal values are reported for each i-user.

$$0 \leq P'_{i-ess_{in}}(k) \leq P_{ess_n} \cdot \alpha_{i-ess} \qquad for\ k = 1 : 96 \tag{5.3}$$

$$-P_{ess_n} \cdot (1 - \alpha_{i-ess}) \leq P'_{i-ess_{ab}}(k) \leq 0 \qquad for\ k = 1 : 96 \tag{5.4}$$

Also the state of charge of the ESS has to be controlled, for this purpose a new variable is defined as SoC_i for every user i. In this case Equation 5.5 defines the SoC while Equation 5.6 limits it within its minimum and maximum values.

$$SoC_i(k) = SoC_i(k-1) + \frac{P'_{i-ess_{ab}}(k) + P'_{i-ess_{in}}(k)}{4 \cdot E_{ess_n}} \qquad for\ k = 1 : 96 \tag{5.5}$$

$$SoC_{min} \leq SoC_i(k) \leq SoC_{max} \qquad for\ k = 1 : 96 \tag{5.6}$$

Energy storage system has been operated in order to have the same initial conditions at the beginning of the day, for this reason Equation 5.7 has been introduced.

$$SoC_i(1) = SoC_i(96) \tag{5.7}$$

Regarding the maximum state of charge, even if not appreciable for limited time period, its degradation has been considered accounting Equation 5.8

$$SoC_{max}(k) = SoC_{max_{initial}} - \frac{SoC_{decrease}}{4} \qquad for\ k = 2 : 96 \tag{5.8}$$

where $SoC_{decrease} = 46\mu$ and $SoC_{max_{initial}} = SoC_{max}(1) = 0.9$.

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Particularly, $SoC_{decrease}$ evaluation has been accomplished considering that at the end of the battery life the available capacity of the battery is considered to be lowered by the 80% with respect to the initial one. From this value, a linear $SoC_{max_{decrease}}$ has been considered computed as:

$$SoC_{decrease}(k) = \frac{(1 - 0.8) \cdot (SoC_{max_{initial}} - SoC_{start})}{lifeyears \cdot 365 \cdot 96}$$

it is clear that the effect of this worsening is not observable moving from one time interval to another but, considering a simulation range of some years it could be appreciated.

A further constrain has been added to limit the battery cycles per day, this to avoid that the maximum number of cycles occurs before the maximum lifetime of the battery; constraint is reported in Equation 5.9.

$$\frac{\sum_{k=1}^{96}(P_{i-ess_{in}}(k) - P_{i-ess_{ab}})}{4 \cdot 2 \cdot E_{ess_n} \cdot (SoC_{max} - SoC_{min})} \leq \frac{lifecycles}{lifeyears \cdot 365} \tag{5.9}$$

Finally, since the ESS is characterized by a round trip efficiency, Equations 5.10 and 5.11 are needed in order to relate the power values at the battery terminals to the power value at the common bus.

$$P'_{i-ess_{in}}(k) = P_{i-ess_{in}}(k) \cdot \eta_d \tag{5.10}$$

$$P'_{i-ess_{ab}}(k) = \frac{P_{i-ess_{ab}}(k)}{\eta_c} \tag{5.11}$$

In this work η_c and η_d, that are respectively the charging and discharging efficiencies of the storage system, have been chosen equal to $\eta_c = \eta_d = \sqrt{RTE} = 0.95$.

Grid constraints With reference to the grid a classical 3 kW energy supply has been considered, therefore this has been considered has the power limit, $P_{grid_{max}}$. For every time interval, Equations 5.12 and 5.13 result defined for every i-user.

$$0 \leq P_{i-grid_{in}}(k) \leq P_{grid_{max}} \cdot \alpha_{i-grid} \qquad for\ k = 1:96 \tag{5.12}$$

$$-P_{grid_{max}} \cdot (1 - \alpha_{i-grid}) \leq P_{i-grid_{ab}}(k) \leq 0 \qquad for\ k = 1:96 \tag{5.13}$$

Where $P_{i-grid_{in}}(k)$ and $P_{i-grid_{ab}}(k)$ are respectively the injected and absorbed power by the grid at interval k and the binary variable α_{i-grid} has been defined in order to avoid the power to be injected and absorbed at the same time.

Global constraints Finally, it is necessary to mathematical link all the variables together, this is easily done adopting the residential model previously depicted, from a mathematical point of view it is possible to write Equation 5.14.

$$P_{i-grid_{in}}(k) + P_{i-grid_{ab}}(k) + P_{i-solar}(k) + \tag{5.14}$$

$$+ P_{i-load}(k) + P_{i-ess_{in}}(k) + P_{i-ess_{ab}}(k) = 0 \qquad for\ k = 1:96 \tag{5.15}$$

5.3.1.2 Commercial

The same mathematical analysis done for residential units is now carried out for the commercial ones, the considered model is the one represented in Figure 5.5.

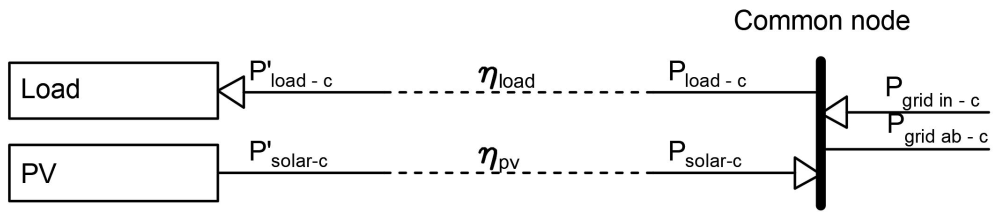


Figure 5.5: Commercial unit model

Load Reference profile for the commercial unit is reported in Figure 5.6.

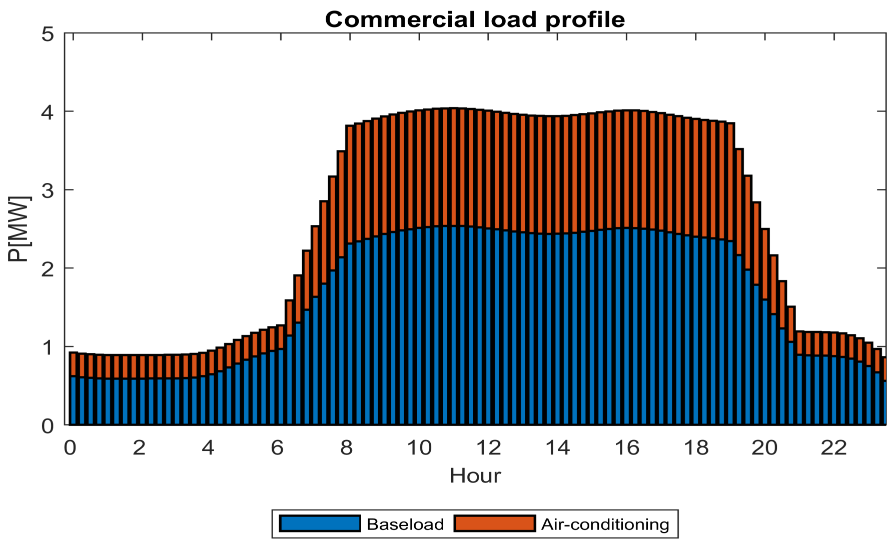


Figure 5.6: Commercial load profile

At each relevant period has been associated an absorbed power, mathematically:

$$P_{load-c}(t) \qquad for\ k = 1:96 \tag{5.16}$$

This profile has been obtained summing the profiles associated to:

- 60 retail shops, each of them characterized by a power profile as shown in Figure 5.7;

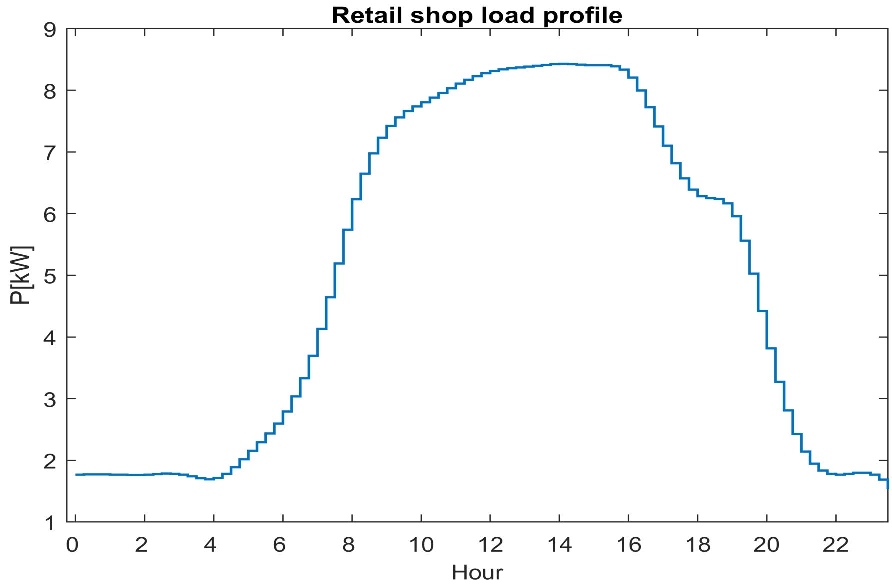


Figure 5.7: Retail shop profile

- 10 restaurants, each of them characterized by a power profile as shown in Figure 5.8;

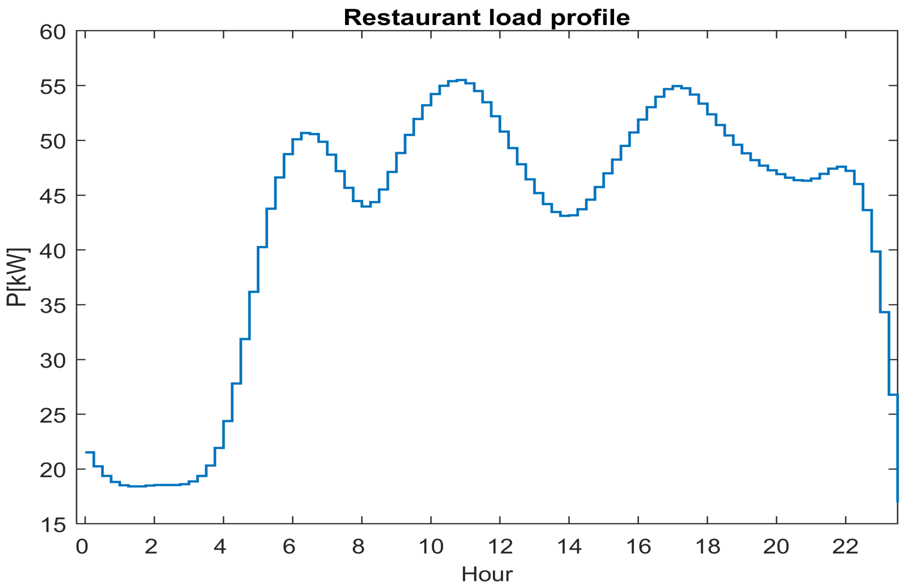


Figure 5.8: Restaurant load profile

- Building air conditioning profile, characterized by a power profile as shown in Figure 5.9.

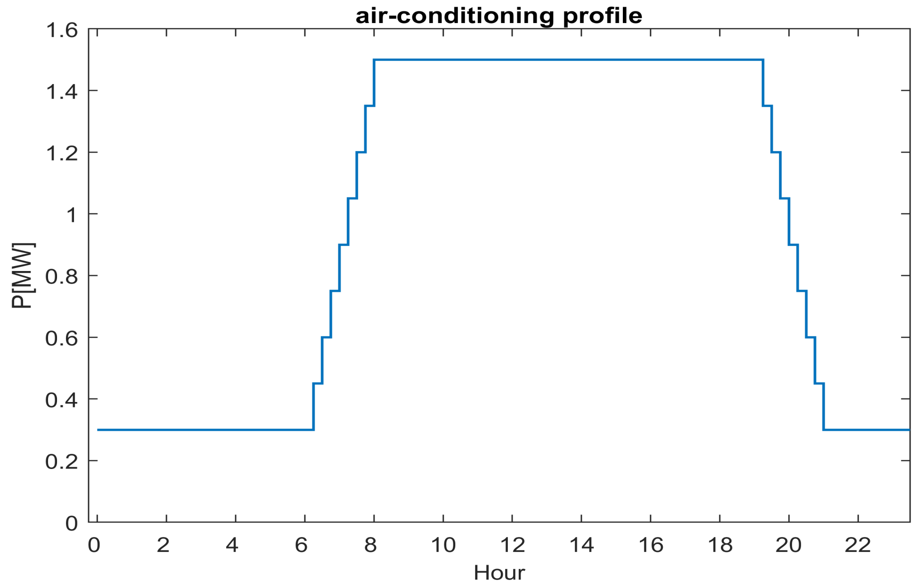


Figure 5.9: Air-conditioning profile

Solar Plant The unit installs a PV park of 500 kW, and it is characterized by a power profile as depicted in Figure 5.10.

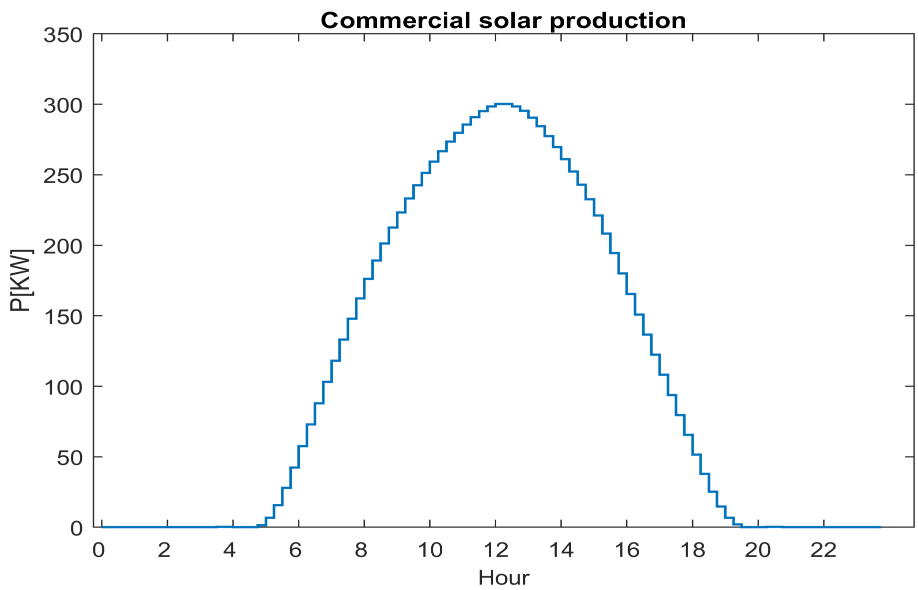


Figure 5.10: Commercial solar production

These profile has been retrieved has done for the residential unit profiles, the mathematical formulation is:

$$P_{solar-c}(k) \qquad for\ k = 1:96 \tag{5.17}$$

Grid constraints With reference to the grid, power limitations are reported in Equations 5.18 and 5.19 has done for residential case, it is clear that grid power limits are higher, particularly they have been considered equal to $P_{grid_{max}-c} = 10\,MW$.

$$0 \leq P_{grid_{in}} - c(k) \leq P_{grid_{max-c}} \cdot \alpha_{grid-c} \qquad for\; k = 1:96 \tag{5.18}$$

$$-P_{grid_{max}-c} \cdot (1 - \alpha_{grid-c}) \leq P_{grid_{ab}-c}(k) \leq 0 \qquad for\; k = 1:96 \tag{5.19}$$

Where $P_{grid_{in}} - c(k)$ and $P_{grid_{ab}-c}(k)$ are respectively the injected and absorbed powers by the grid of the commercial user at time interval k and the binary variable α_{grid-c} has been defined in order to avoid the power to be injected and absorbed at the same time.

Global constraints Finally, it is necessary to mathematical link all the variables together, this is easily done adopting the commercial model previously depicted, from a mathematical point of view it is possible to write Equation5.20.

$$P_{grid-c_{in}} + P_{grid-c_{ab}} + P_{solar-c} + P_{load-c} = 0 \tag{5.20}$$

5.3.2 Objective function

As mentioned, the goal of these optimization is to retrieve a reference profile for each considered unit, these will be exploited later when MB optimization will be done. With this goal, for each residential unit and for the commercial one, the objective function has been formulated as shown in Equation 5.21 and then solved by the optimizer.

$$min(\frac{\sum_{k=1}^{96}(P_{grid-injected}(k) \cdot C_{in}(k) + P_{grid-absorbed}(k) \cdot C_{ab}(k))}{4}) \tag{5.21}$$

Where, depending on the type of unit, $P_{grid-injected}(k)$ and $P_{grid-absorbed}(k)$ refers respectively to $P_{grid-c_{in}}$, $P_{grid-c_{ab}}$ or $P_{i-grid_{in}}$, $P_{i-grid_{ab}}$. The parameters $C_{in}(k)$ and $C_{ab}(k)$ are respectively the prices that, at time interval k, a unit has to pay to or receive from its energy retailer. In this case the goal is to minimize the cost for supply the defined load for each unit. It is worth to recall that the injected power by the grid is the one that the user has to pay to its energy retailer while, the absorbed one, is the one for which the unit is paid. In fact, the injected power by the grid into the common node is the one that is absorbed by the user. On the contrary, the absorbed power by the grid is the one that the user is injecting into the common node. According to the adopted conventions, the injected power is a positive quantity that increases the objective function while, the absorbed one, is a negative quantity that decreases the objective function. The minimization problem is therefore correctly represented, considering that the parameters C_{in} and C_{ab}, which accounts for the energy price, have been modeled as positive quantities, namely:

- $C_{in}(k)$ is the price, at interval k, that a unit has to pay when grid injects power, it is expressed in €/kWh; as reported in ARERA website, $C_{in}(k)$ depends on the considered quarter as shown in Table 5.1:

Quarter	€/kWh
J, F, M	0.2063
A, M, J	0.1898
J, A, S	0.2022
O, N, D	0.1897

Table 5.1: Quarterly energy prices, ARERA

- $C_{ab}(k)$is the price, at interval k, that a unit receives when grid absorbs power, it is expressed in €/kWh and, as reported in ARERA website, it has been chosen equal to 0.0394 €/kWh;

The factor 4 in the formula is necessary because the power value refers to a 15 minutes interval while the energy price is expressed in €/kWh.

5.3.3 Results and considerations

Since the load profile has been chosen different for all the users, the obtained results are clearly different too. According to the adopted model, Figures 5.11, 5.13, 5.14, 5.15, 5.16, 5.17 are representative of the algorithm output. Particularly it is possible to observe how different configuration are available, namely: both PV and ESS are present in the unit, only the PV is installed or neither PV and ESS are present. Of course, the daily energy cost varies consistently between different considered scenarios:

1. Both PV and ESS installed: the average summer daily bill consist of -0.09€, while, during winter it results of 0.87 €;

2. Only PV is installed: the average summer daily bill consist of 0.61€, while, during winter it results of 1.26 €;

3. Neither PV and ESS installed: the average summer daily bill consist of 2.75€, while, during winter it results of 1.65 €;

With reference to Figure 5.11, some detailed considerations are reported, the same analysis method can be adopted for the other reported profiles. In this thesis it has not been considered relevant to carry out this evaluation repeatedly for all the depicted profiles.

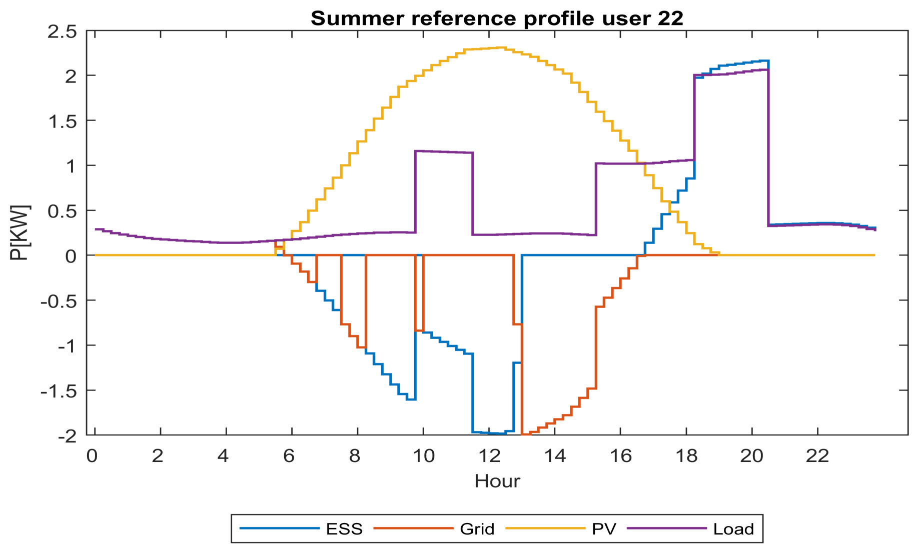


Figure 5.11: Summer, reference profile, PV + ESS

Focusing on the load profile, represented as a positive quantity in these figures, it can be clearly distinguished between the base-load and the time periods in which the dish-washer, the washing-machine and the air-conditioner are turned on. In this case, according to their previously reported cycles duration, it is possible to state that the washing-machine and the dish-washer are turned on respectively at 9.45 a.m and 6.15 p.m while, the air-conditioner, is turned on at 3.15 p.m. With reference to the solar production, represented by a positive quantity, the common bell-shaped profile can be appreciated, pointing out that the production is lower with respect to the nominal power of the PV plant, which is 4 kW. This is related with the considered solar irradiation, strictly dependent on the geographical area in which the units are localized. For what concerns the energy storage system, in Figure 5.12 the SoC behaviour is reported. It is possible to point out that, when the solar production is higher than the load, the SoC tends to increase; in fact the ESS is charged during these periods and this is represented by a negative power flow in the figure. Focusing on the SoC curve, it matches with the introduced constraints on the maximum number of cycles per day and the minimum and maximum allowed values. Particularly, in this case, the SoC maximum level is not even reached, the reason is strictly related to load profile and to the constraint that imposes the SOC level to be the same at the begging and the end of each day. It is evident how the load is entirely supplied by the ESS during the last hours of the day; this allows the ESS to reach the initial SoC at the end of the day. If the SoC had been higher before these last day hours, in order to allow the ESS to discharge enough power to reach the initial condition, the load should have been higher. Finally, it is possible to exploit the represented profiles to highlight how the efficiency of the ESS affects its behaviour. With this regard, from 10 p.m on, it is clear that the energy injected by the ESS is higher than the one absorbed by the load. This is due to the losses of the storage system converter, and it results clear that the depicted one is the power flow at battery terminals and not at the common node.

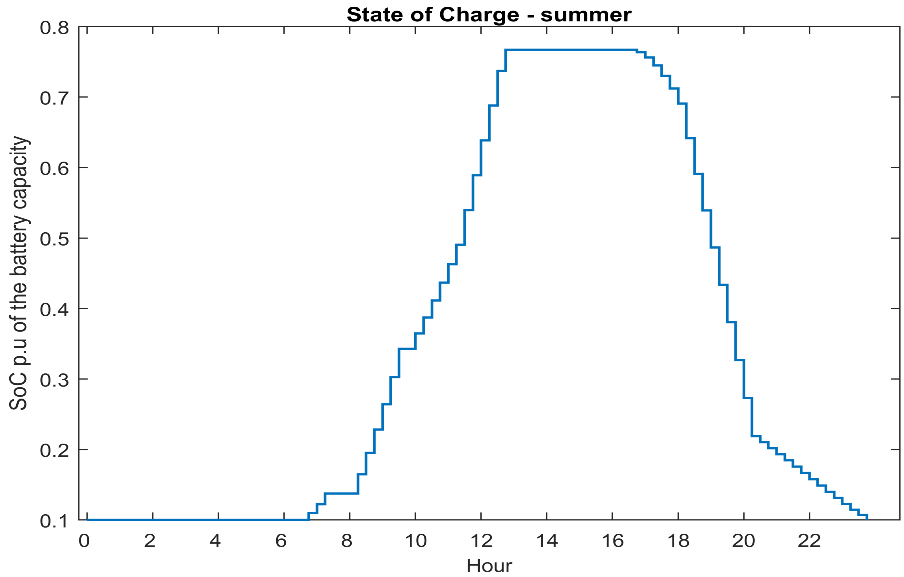


Figure 5.12: Summer, SoC behaviour, user 22

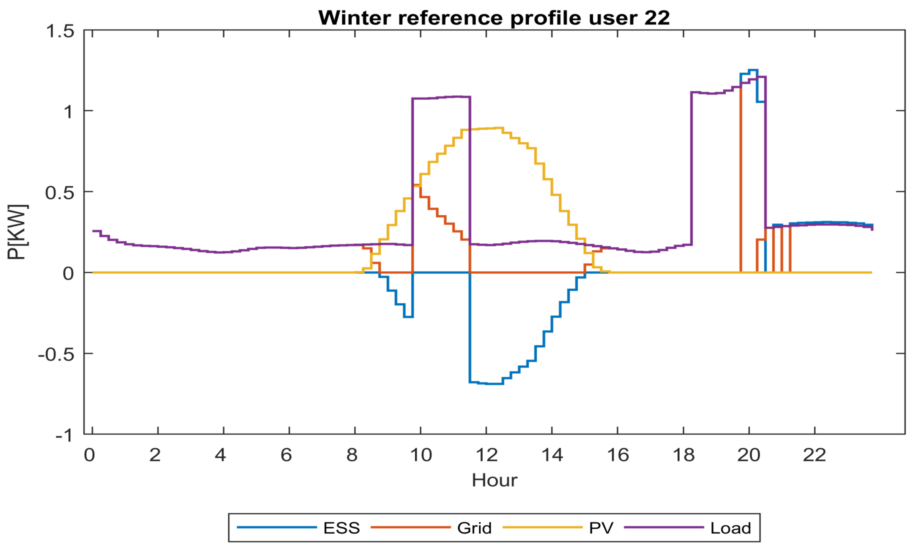


Figure 5.13: Winter, reference profile, PV + ESS

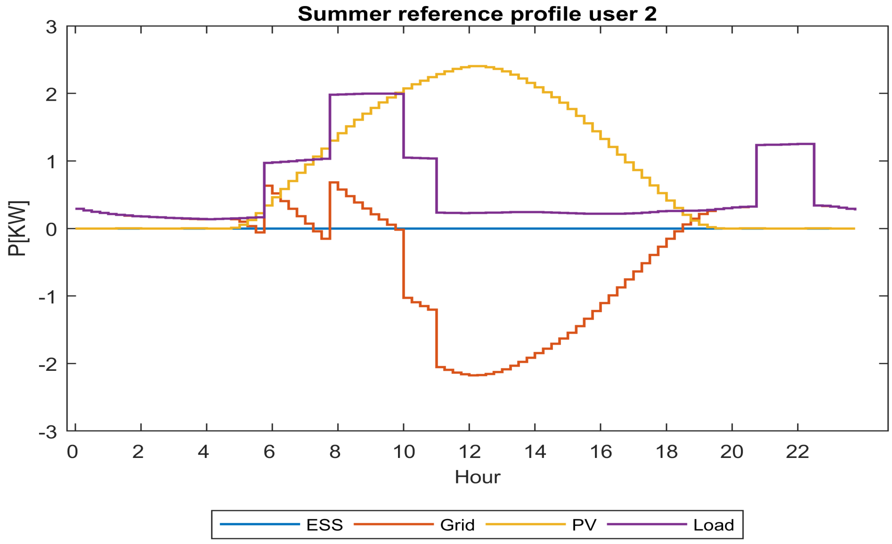


Figure 5.14: Summer, reference profile, PV

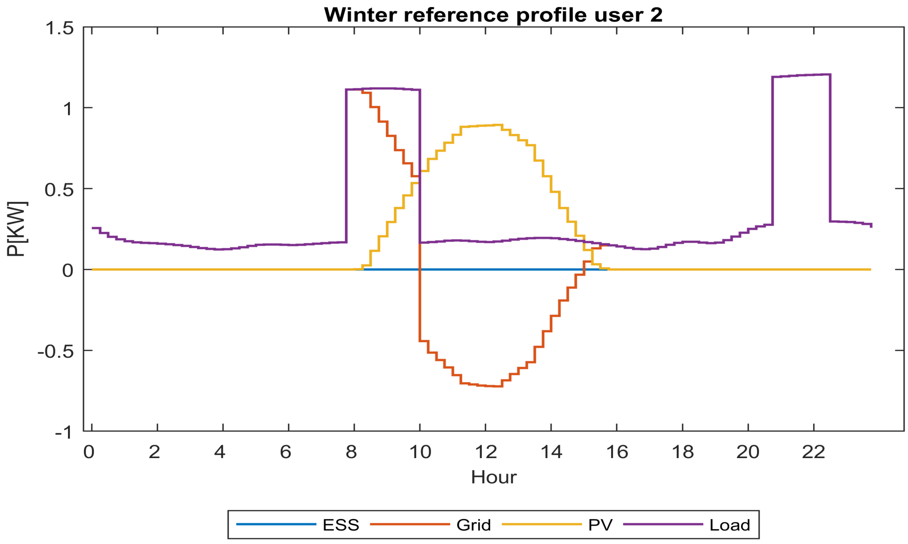


Figure 5.15: Winter, reference profile, PV

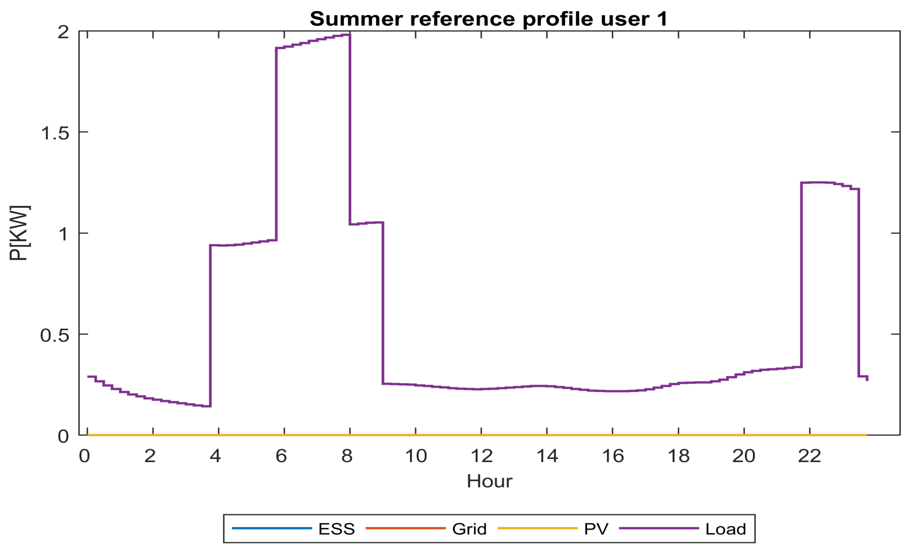


Figure 5.16: Summer, reference profile, no PV, no ESS

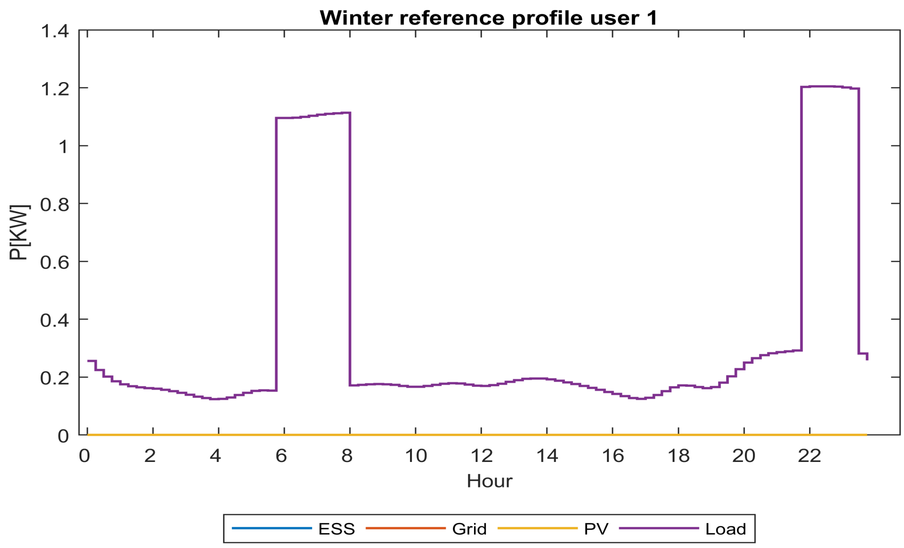


Figure 5.17: Winter, reference profile, no PV, no ESS

With reference to the residential units, during winter it is possible to observe a PV production decrease. On the other hand, load increases in certain time intervals because of the bathroom heaters higher absorption, but on the opposite, due to the lack of air-conditioner cycle, it decreases in others.

Concerning the commercial unit, the summer and winter considered power profiles are reported in Figures 5.18 and 5.19.

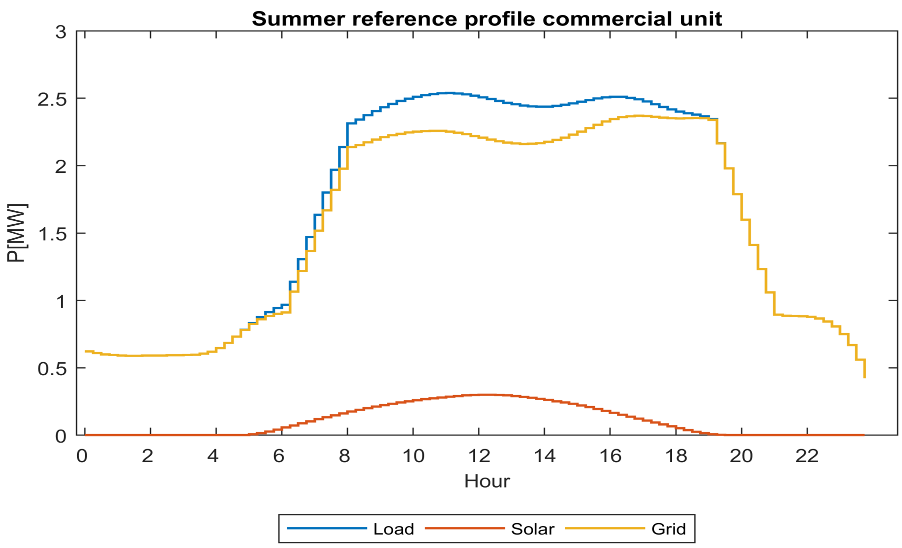


Figure 5.18: Summer, reference profile of commercial unit

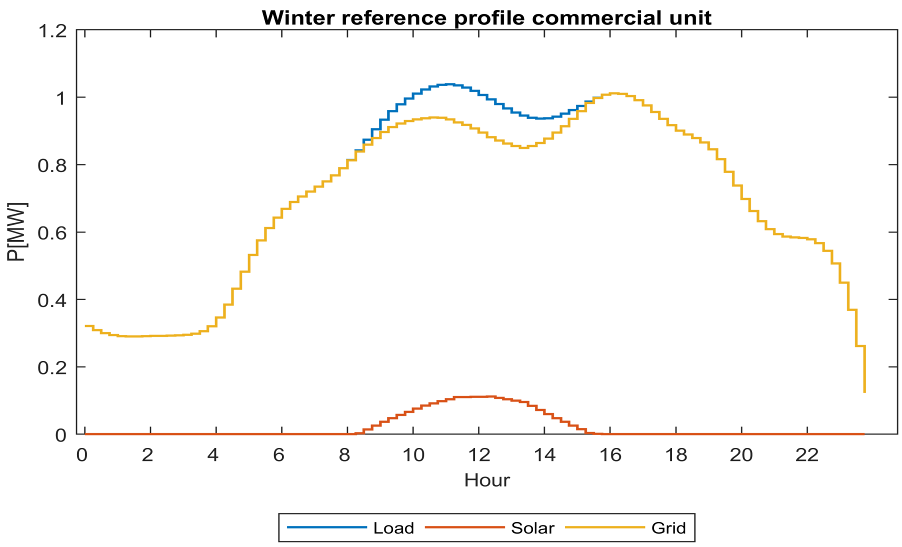


Figure 5.19: Winter, reference profile of commercial unit

As depicted, during colder seasons, air-conditioner cycle is absent; therefore, the load absorption observes a huge decrease with respect to summer power profile. With this regard, it can be marked the relevant role covered by the air-conditioning systems in large buildings. Finally, both during summer and winter periods, the absorbed energy from the grid decreases when the solar production increases.

5.4 Balancing market optimization

This is the heart of the work, in which actually the final results will be obtained. Even though the analyzed scenarios are two, as already introduced, the devices model and mathematical formulations are the same for both of them, the only differences regard aggregator constraints and objective functions.

5.4.1 Devices model

5.4.1.1 Residential

First step is to introduce the model adopted for the MB residential units description; it is is shown in Figure 5.20.

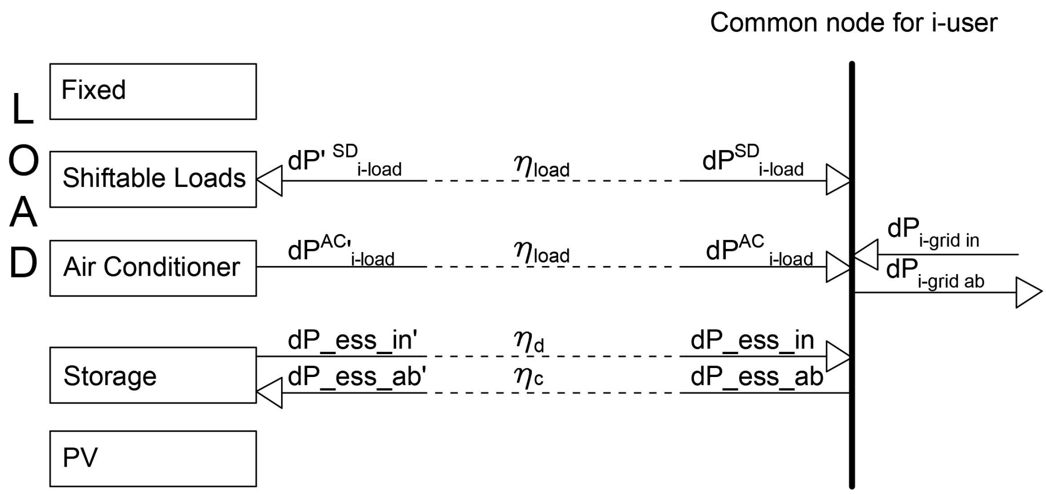


Figure 5.20: MB residential unit model.

The previous optimization guarantees to find a reference profile, in which a power absorption or injection is scheduled for every k-interval. With respect to it, the *maximum-delta-power* allowed variations are defined. They are computed as the gap between the scheduled profiles and the power limits of every device. *Maximum-delta-power* evaluation, that has to be accomplished for every user i, is presented in Table 5.2, it is important to recall that, compared to the preliminary optimization, *load-shifting* and *load-curtailment* can be applied to dish-washers, washing-machines and air conditioning.

$\Delta^{DEVICE}_{i-max_{in}}(k)$ and $\Delta^{DEVICE}_{i-max_{ab}}(k)$ identify the power increase and decrease that is possible to achieve with respect to the reference profile in the specific k-interval for user i. Depending on the considered device they are computed differently. The apex «SD» adopted in the variable P^{SD}_{cycle} identify the shiftable load, it can be the dish-washer or the washing-machine. Clearly, the fix load does not allow any variation;

	$\Delta^{DEVICE}_{i-max_{in}(k)}$	$\Delta^{DEVICE}_{i-max_{ab}(k)}$
Fixed load	0	0
Load curtailment	$P_{max_{decrease}}(k)$	$-P_{max_{increase}}(k)$
Load shifting	$P^{SD}_{cycle}(k)$	$-P^{SD}_{cycle}(k),\ for\ k > t_{end}(k)$
ESS	$P_{ess_n} - P_{i-ess_{in}}(k) - P_{i-ess_{ab}}(k)$	$-P_{ess_n} + P_{i-ess_{in}}(k) + P_{i-ess_{ab}}(k)$
Grid	$P_{grid_{max}} - P_{i-grid_{in}}(k) - P_{i-grid_{ab}}(k)$	$-P_{grid_{max}} + P_{i-grid_{in}}(k) + P_{i-grid_{ab}}(k)$

Table 5.2: Maximum variation allowed for MB optimization

all the values represented in the previous table have to be defined for each unit, both residential and commercial.

Particularly, in order to clarify this process, an example is reported in Figure 5.21 with reference to a storage system.

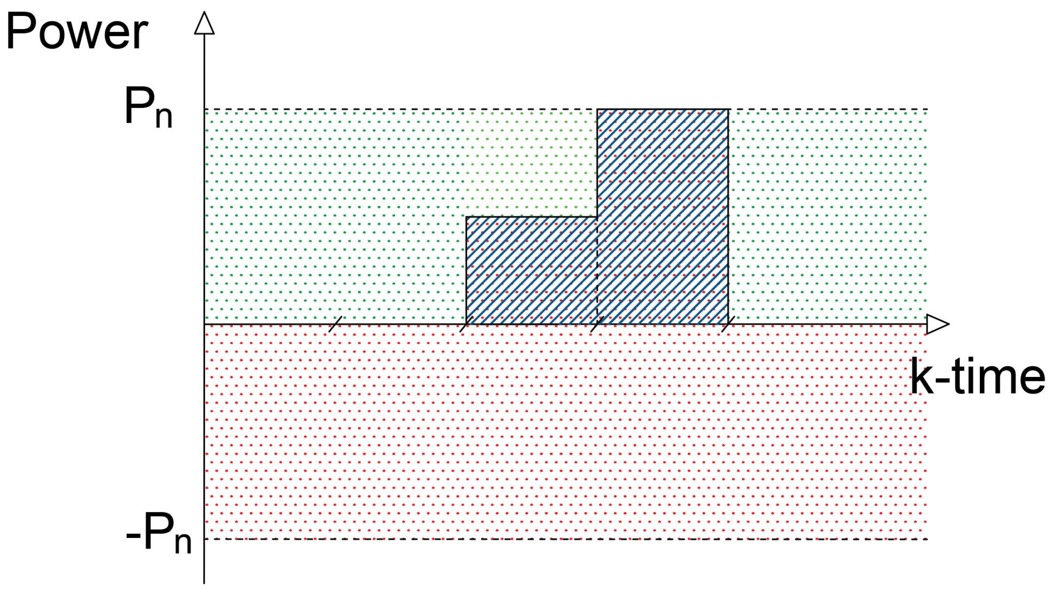


Figure 5.21: *Delta-power* evaluation example.

If the blue area is assumed as the reference power profile for the storage system, defined for each k-time, and P_n is the nominal power of the battery, it is possible to realize that, with respect to the reference profile it is still possible to increase power injection of the ESS by a quantity equal to the green dotted one, while it is possible to decrease power injection by a quantity equal to the red dotted one. These quantities are identified with $\Delta^{ess}_{max_{in}}$ and $\Delta^{ess}_{max_{ab}}$ respectively.

In the following, concerning constant parameters, namely: efficiencies, nominal powers, nominal energies and SoC limits they all equal the ones introduced in the reference profile computation, in fact, the considered units are the same.

Load Shifting Dish-washers and washing-machines are home appliances that allow to shift their cycle from one day period to another one, keeping its continuity in time. This means that once the cycle has started, it cannot be interrupted. In Figure 5.22 is depicted an example showing a load shift of a generic load.

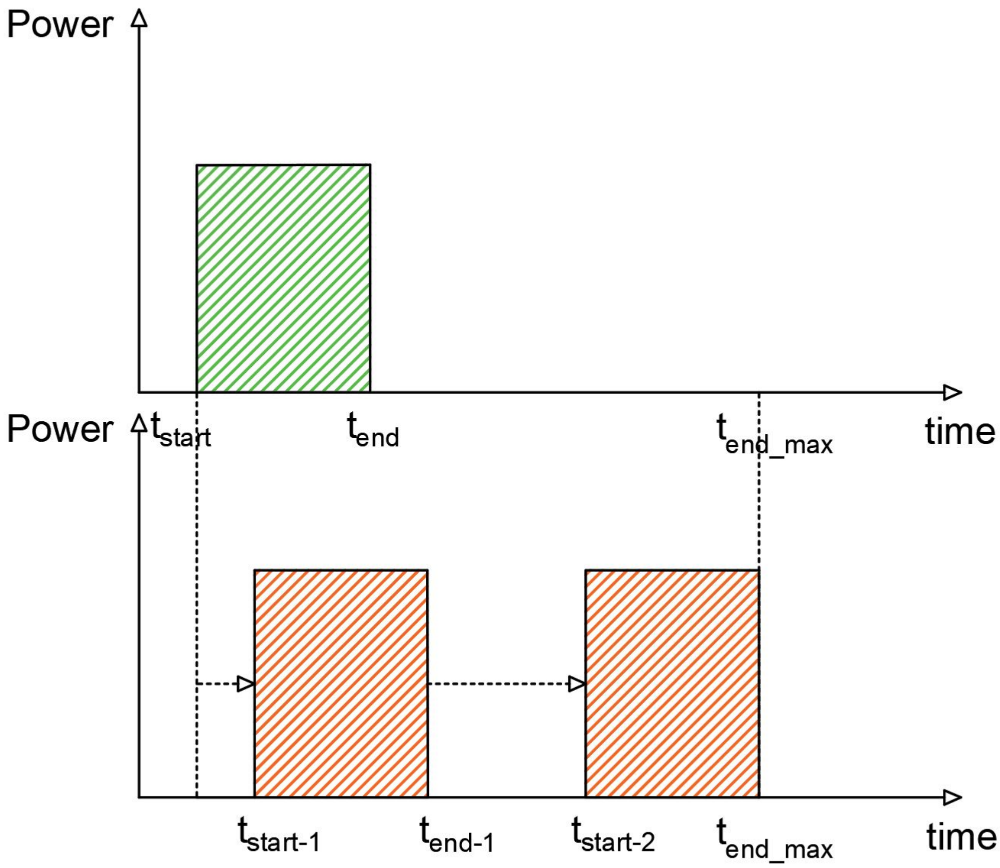


Figure 5.22: Load Shifting of a generic load.

In this work load can be shifted forward until its end-time coincides with the maximum end-time defined by the user, in other words this mean that a user is not interested at which time the cycle will start but he only cares that, at a given time, the cycle has ended.

From a mathematical point of view this problem can be formulated for each shiftable device identified by the apex «*SD*» owned by i-user identified by the subscript «i»; therefore, in the following, the apex «SD» means that the variable has to be defined both for the dish-washer (DW) and for the washing-machine (WM). The formulation has to be structured as follows:

- The reference profile has to be considered, a load-shifting is represented by a load decrease and a load increase, as depicted in Figure 5.23 introducing 15 minutes discrete time steps as adopted in the optimization; moreover, for the sake of a better comprehension, reference can be made to Figure 5.24 where variables are depicted along with their value, considering as an example a delta=6 and a shifting time of 2.

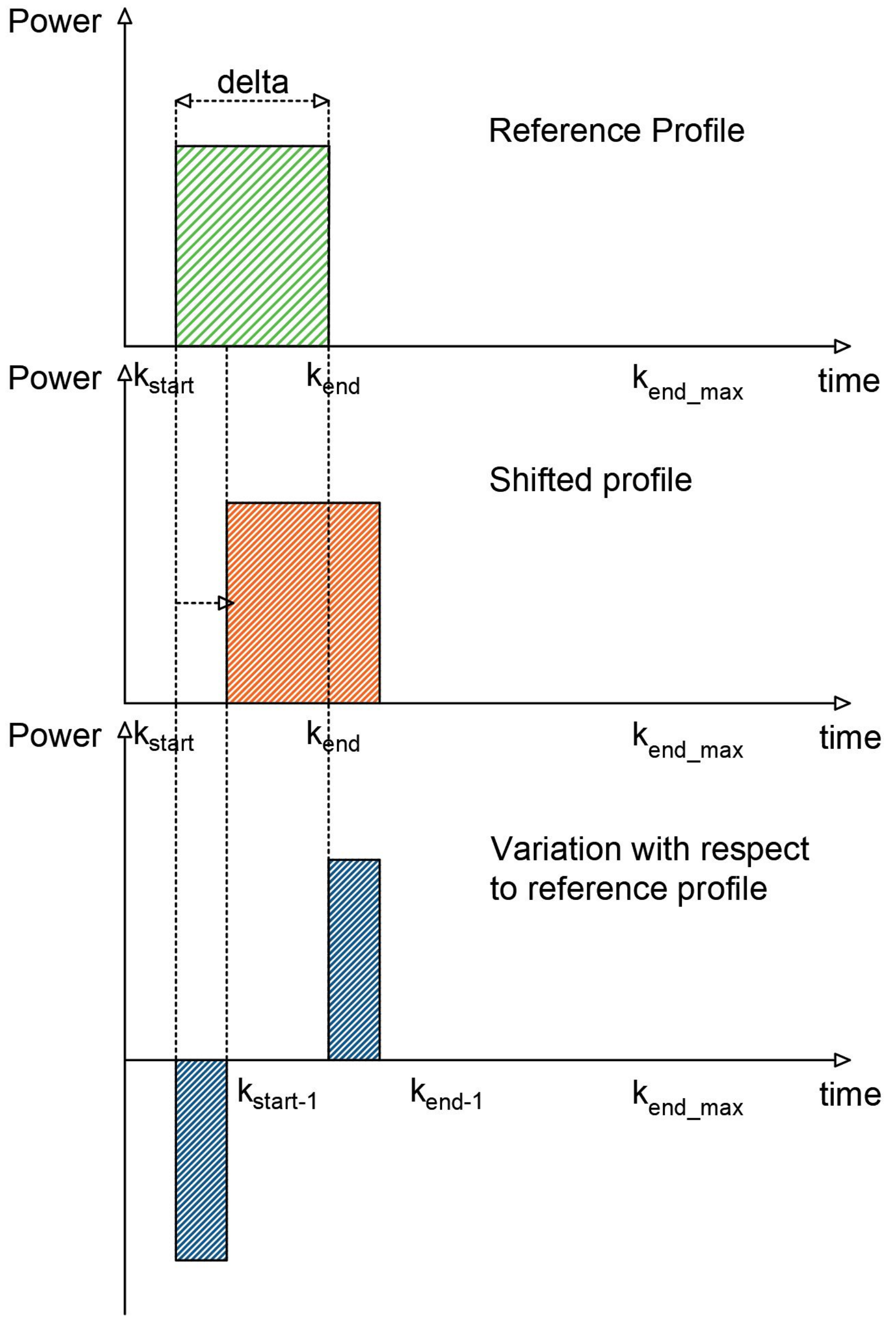


Figure 5.23: Load Shifting of a generic load.

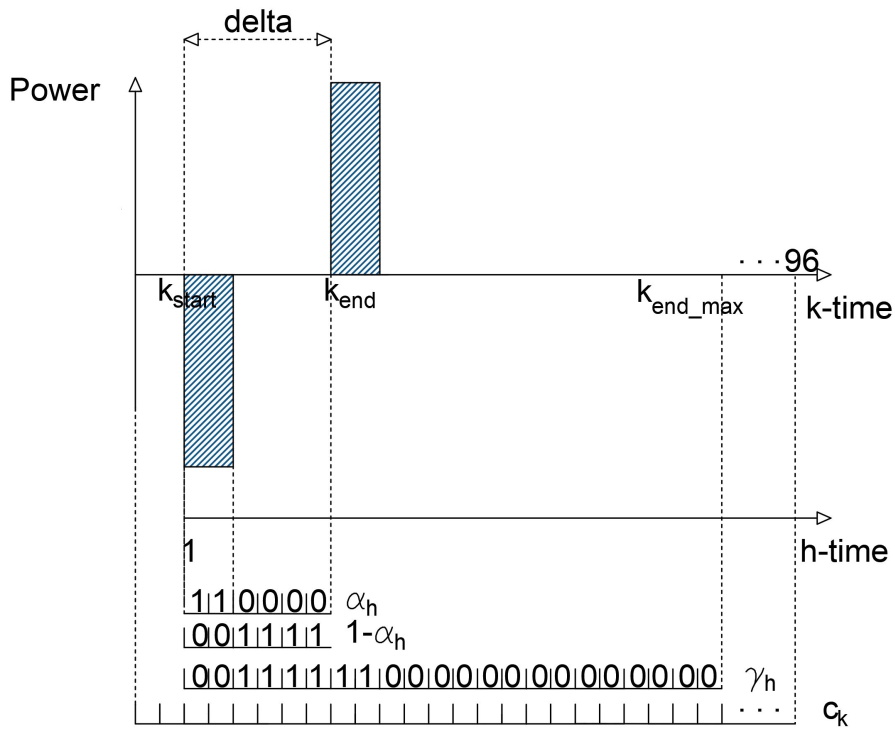


Figure 5.24: Load Shifting of a generic load, variable definition and example.

It is possible to observe that the cycle elapses a time *delta* and it has been shifted from k_{start} *to* $k_{start-1}$, then, the variation occurring between the reference and the new profile is reported; this is important since the MB optimizer deals with power variation profiles. The first mathematical constraints has to be taken into account to introduce the possibility to reduce the load with respect to the baseline. This is carried out exploiting a binary variable, α_i^{SD}, that equals 1 if and only if the load is decreased with respect to the reference profile, the Equation 5.22 ensures that if the load is shifted it is shifted starting from the beginning of the cycle:

$$\alpha_i^{SD}(h) \leq \alpha_i^{SD}(h-1) \quad for\, h = 2 : delta^{SD} \tag{5.22}$$

- The new profile is identified by a variable dP_{i-load}^{SD} that is subjected to constraints of Equation 5.23 and Equation 5.24 that assign the power values to the new profile; the former states that before the reference starting time ($k_{i-start}^{SD}$) and after the maximum end-time ($k_{i-end_{max}}^{SD}$) of user i, the variation with respect to the reference profile has to be zero (in fact, only forward shifting is allowed and the maximum end-time chosen by the user have to be respected), the latter defines the variation occurred if a shifting has been applied.

$$dP_{i-load}^{SD}(k) = 0 \quad for\, k = 1 : k_{i-start}^{SD} - 1\, and\, for\, k = k_{i-end_{max}+1}^{SD} : 96 \tag{5.23}$$

$$dP_{i-load}^{SD}(k) = -P_{cycle}^{SD} \cdot \alpha_i^{SD}(k - k_{i-start}^{SD} + 1) \qquad (5.24)$$
$$for\, k = k_{i-start}^{SD} : k_{i-start}^{SD} + delta^{SD} - 1$$

The variable $dP_{i-load}^{SD}(k)$ is the injected power variation, of the considered controllable device «SD», with respect to its reference profile at time interval k.

- Up to now, only the power decrease has been evaluated, it is important to mathematically point out that this has to be compensated by a power increase. Particularly, it can be realized that α_i^{SD} is a vector that equals 1 only when the cycle has been curtailed with respect to the reference one, therefore, if $1 - \alpha_i^{SD}$ is considered, it equals one only when the cycle has not been changed with respect to the reference profile. This allow us to take into consideration if the cycle has been shifted by a time equal/higher than delta or lower than delta, in the former case, α_i^{SD} always equals 1, in the latter not. Particularly, in this case, the load increase with respect to the reference profile has to occur immediately after the k_{end}, as depicted in the considered example. To take into account that the cycle runs for the whole time, without interruptions, a binary variable has been defined ($\gamma_i^{SD}(h)$), it equals one when the cycle is running, therefore, its sum has to be equal to delta has specified by Equation 5.25.

$$\sum_{h=1}^{k_{i-end_{max}}^{SD} - k_{i-start}^{SD} + 1} \gamma_i^{SD}(h) = delta^{SD} \qquad (5.25)$$

where h identifies a time interval.

Additionally, if the cycle is shifted by a quantity lower than delta, it implicitly has defined a time in which, with respect to the reference case, no variation occurs and therefore the power absorption remains unaltered, this is defined by variable $1 - \alpha_i^{SD}$. When it equals 1, the cycle is running as in reference case, therefore it has to be accounted in variable γ_i^{SD}; in order to do this, variable γ_i^{SD} can be defined as shown in Equation 5.26

$$\gamma_i^{SD}(h) = 1 - \alpha_i^{SD}(h) \quad for\, h = 1 : delta^{SD} \qquad (5.26)$$

Always about γ_i^{SD} it has to be defined the constraints that sets that the cycle can not be interrupted, this can be done exploiting Equation 5.27

$$\gamma_i^{SD}(h) \geq \gamma_i^{SD}(h*) - \gamma_i^{SD}(h*-1) \qquad (5.27)$$
$$for\, h = h* : h* + delta^{SD} - 1$$
$$for\, h* = 2 : k_{i-end_{max}}^{SD} - k_{i-start}^{SD} - delta^{SD} + 2$$

it can be realized that $\gamma_i^{SD}(h*) - \gamma_i^{SD}(h*-1)$ equals 1 only when γ_i^{SD} moves from 0 to 1, that identifies the time in which the cycle begins, from that moment on γ_i^{SD} has to be higher or equal to 1 for at least delta time intervals that becomes, thanks to 5.25: γ_i^{SD} has to be higher or equal to 1 for delta time intervals.

- Finally, the variation power profile has to be defined, it results in Equation 5.28

$$dP_{i-load}^{SD}(k) = P_{cycle}^{SD} \cdot \gamma_i^{SD}(k - k_{i-start}^{SD} + 1) \qquad (5.28)$$
$$for\, k = k_{start}^{SD} + delta_i^{SD} : k_{i-end_{max}}^{SD}$$

If desired, it is possible to split variable dP_{i-load}^{SD} into a positive $(dP_{i-load_{in}}^{SD}(k))$ and a negative $(dP_{i-load_{ab}}^{SD}(k))$ term, it is sufficient to add the constraints of Equation 5.29, Equation 5.30 and Equation 5.31, introducing a binary variable ϕ_i^{SD} defined for $k = 1 : 96$.

$$dP_{i-load}^{SD}(k) = dP_{i-load_{in}}^{SD}(k) + dP_{i-load_{ab}}^{SD}(k) \quad for\, all\, k = 1 : 96 \qquad (5.29)$$

$$\phi_i^{SD}(k) \cdot \Delta P_{i-max_{in}}^{SD} \geq dP_{i-load_{in}}^{SD}(k) \geq 0 \quad for\, all\, k = 1 : 96 \qquad (5.30)$$

$$(1 - \phi_i^{SD}(k)) \cdot \Delta P_{i-max_{ab}}^{SD} \leq dP_{i-load_{ab}}^{SD}(k) \leq 0 \quad for\, all\, k = 1 : 96 \qquad (5.31)$$

$\Delta P_{i-max_{in}}^{SD}$ and $\Delta P_{i-max_{ab}}^{SD}$ are the maximum power that can be decreased or increased with respect to the reference cycle, in this case they both equal the average cycle power P_{cycle}^{SD}. However, for the purposes of these work, load power variation has been described by a unique variable dP_{i-load}^{SD} which can assume both positive and negative values.

Load Curtailment As previously introduced, it is possible to modulate the power absorption of the air-conditioner. This simulates the flexibility provided by the units thermal inertia. Mathematically, it can be represented by Equation 5.32, which implies that, for each time period k, the power increase or decrease cannot be higher than a certain value.

$$\Delta_{i-max_{ab}}^{AC}(k) \leq dP_{i-load}^{AC}(k) \leq \Delta_{i-max_{in}}^{AC}(k) \quad for\, all\, k = 1 : 96 \qquad (5.32)$$

where $dP_{i-load}^{AC}(k)$ is the power variation at time interval k with respect to the air-conditioner reference profile of user i while $\Delta_{i-max_{ab}}^{AC}(k)$ and $\Delta_{i-max_{in}}^{AC}(k)$ respectively identify the limits of this power variation.

In order to avoid that the energy consumption differs from the one associated to the average cycle, that coincides with the reference one, Equation 5.33 is necessary.

$$\sum_{k=1}^{96} dP_{i-load}^{AC}(k) = 0 \tag{5.33}$$

Finally, Equation 5.34 implies that with respect to the reference starting and ending times the cycle can be started one hour and a half earlier and/or ended one hour and a half later.

$$dP_{i-load}^{AC}(k) = 0 \qquad for\, k = 1 : k_{i-start}^{AC} - delay\, and\, for\, k = k_{i-end}^{AC} + delay : 96 \tag{5.34}$$

where $k_{i-start}^{AC}, k_{i-end}^{AC}$ refer to the starting and ending cycle times as scheduled in the reference profile for each i-user; *delay*, instead, is the maximum delay time that in this case has been chosen equal to one hour and a half for every residential user.

Solar plant Energy produced by photovoltaic plant is assumed constant and therefore no variation can occur.

Energy Storage System As for the reference profile computation, also in this case the same constraints have to be applied, the only difference is that used variables are the power variations instead of powers. Therefore, introducing the binary variables α_{i-ess}, ESS constraints are represented by Equations 5.35 and 5.36 that limit the variation within the allowed limits.

$$0 \leq dP'_{i-ess_{in}}(k) \leq \Delta_{i-max_{in}}^{ess} \cdot \alpha_{i-ess} \qquad for\, all\, k = 1 : 96 \tag{5.35}$$

$$\Delta_{i-max_{ab}}^{ess} \cdot (1 - \alpha_{i-ess}) \leq dP'_{i-ess_{ab}}(k) \leq 0 \qquad for\, all\, k = 1 : 96 \tag{5.36}$$

where $dP'_{i-ess_{in}}(k)$ and $dP'_{i-ess_{ab}}(k)$ respectively represent the power variation of the injected and absorbed power by the ESS of user i at battery terminals.

For what concerns the SoC Equations 5.37 and 5.38 have to be considered.

$$SoC_i(k) = SoC_i(k-1) - \frac{P'_{i-ess_{ab}}(k) + P'_{i-ess_{in}}(k) +}{4 \cdot E_{ess_n}} \tag{5.37}$$
$$\frac{+dP'_{i-ess_{in}}(k) + dP'_{i-ess_{ab}}(k)}{4 \cdot E_{ess_n}} \qquad for\, all\, k = 1 : 96$$

$$SoC_{min} \leq SoC_i(k) \leq SoC_{max} \qquad for\ all\ k = 1:96 \tag{5.38}$$

Energy storage system has been operated in order to have the same initial conditions at the beginning of the day, for this reason Equation 5.39 has been introduced.

$$SoC_i(1) = SoC_i(96) \tag{5.39}$$

As for the previous case, also Equation 5.40 is considered in case of long term evaluations.

$$SoC_{max}(k) = SoC_{max_{initial}} - \frac{SoC_{decrease}}{4} \qquad for\ k = 2:96 \tag{5.40}$$

To limit the per day cycles, constraints represented in Equation 5.41 is required.

$$\frac{\sum_{k=1}^{96}(P_{i-ess_{in}}(k) - P_{i-ess_{ab}} + dP'_{i-ess_{in}}(k) - dP_{i-ess_{ab}}(k))}{4 \cdot 2 \cdot E_{ess_n} \cdot (SoC_{max} - SoC_{min})} \leq \frac{lifecycles}{lifeyears \cdot 365} \tag{5.41}$$

Finally, relation between common node and battery terminals variables is reported in Equations 5.42 and 5.43

$$dP'_{i-ess_{in}}(k) = dP_{i-ess_{in}}(k) \cdot \eta_d \tag{5.42}$$

$$dP'_{i-ess_{ab}}(k) = \frac{dP_{i-ess_{ab}}(k)}{\eta_c} \tag{5.43}$$

where $dP_{i-ess_{in}}(k)$ and $dP_{i-ess_{ab}}(k)$ respectively represent the power variation of the injected and absorbed power by the ESS of user i at the common node.

Grid constraints Also for the exchanged power by the grid the power limitations has to be respected introducing constraints reported in Equations 5.44 and 5.45.

$$0 \leq dP_{i-grid_{in}}(k) \leq \Delta^{grid}_{i-max_{in}} \cdot \alpha_{i-grid} \qquad for\ k = 1:96 \tag{5.44}$$

$$\Delta^{grid}_{i-max_{ab}} \cdot (1 - \alpha_{i-grid}) \leq dP_{i-grid_{ab}}(k) \leq 0 \qquad for\ k = 1:96 \tag{5.45}$$

Also in this case binary variable α_{i-grid} has been defined in order to avoid the power to be injected and absorbed at the same time. Variables $dP_{i-grid_{ab}}(k)$ and $dP_{i-grid_{in}}(k)$ are respectively the absorbed and injected power variations of the grid of user i with respect to the reference profile, at time interval k. $\Delta^{grid}_{i-max_{ab}}$ and $\Delta^{grid}_{i-max_{in}}$ are the absorption and injection power variation limits.

Global constraints Power balance, for each i-user has finally to be met, the condition to be respected is reported in Equation 5.20.

$$dP_{i-grid_{in}}(k) + dP_{i-grid_{ab}}(k) - dP^{DW}_{i-load}(k) - dP^{WM}_{i-load}(k)+ \tag{5.46}$$
$$+ dP^{AC}_{i-load}(k) + dP_{i-ess_{in}}(k) + dP_{i-ess_{ab}}(k) = 0 \quad for\, k = 1:96 \tag{5.47}$$

5.4.1.2 Commercial

Same constraints reported for residential units keep truth for the commercial ones, in this case no shiftable load has been considered, only load curtailment is available. The adopted model is depicted in Figure 5.25.

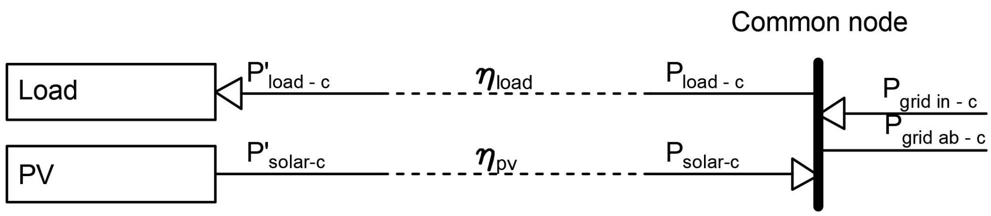


Figure 5.25: MB commercial unit model.

Load Curtailment As done for the residential units, Equations 5.48 has to be applied to guarantee power limitation:

$$\Delta^{AC}_{max_{ab}-c}(k) \leq dP^{AC}_{load-c}(k) \leq \Delta^{AC}_{max_{in}-c}(k) \quad for\, k = 1:96 \tag{5.48}$$

where $dP^{AC}_{load-c}(k)$ is the power variation at time interval k of the commercial air-conditioning power profile with respect to its reference profile; $\Delta^{AC}_{max_{ab}-c}(k)$ and $\Delta^{AC}_{max_{in}-c}(k)$ are the power variation limits.

Then, Equation 5.49 ensures the same absorbed energy with respect to the reference profile. In this case, variation can occur all day long, without any constraint regarding the maximum delay time with respect to the reference profile as occurred for the residential case. This choice because in the commercial unit air conditioner is on all day long. Therefore, the values $\Delta^{AC}_{max_{ab}-c}$ and $\Delta^{AC}_{max_{in}-c}$ have been chosen considering a variation of the 10% with respect to the actual absorbed power as scheduled in the reference profile.

$$\sum_{k=1}^{96} dP^{AC}_{load-c}(k) = 0 \tag{5.49}$$

Solar plant As previously explained, no solar variation has been accounted for.

Grid constraints Grid power limitations are ensured by Equation 5.50 and Equation 5.51.

$$0 \leq dP_{grid_{in}-c}(k) \leq \Delta^{grid}_{max_{in}-c} \cdot \alpha_{grid-c} \qquad for\, k = 1:96 \tag{5.50}$$

$$\Delta^{grid}_{max_{ab}-c} \cdot (1 - \alpha_{grid-c}) \leq dP_{grid_{ab}-c}(k) \leq 0 \qquad for\, k = 1:96 \tag{5.51}$$

The variables $dP_{grid_{in}-c}(k)$ and $dP_{grid_{ab}-c}(k)$ are respectively the injected and absorbed power variation of the commercial unit grid with respect to its reference profile; $\Delta^{grid}_{max_{in}-c}$ and $\Delta^{grid}_{max_{ab}-c}$ are the power variation limits and have been respectively chosen equal to $+20\,MW$ and $-20\,MW$. Also in this case a binary variable (α_{grid-c}) has been introduced so to avoid that injection and absorption occur simultaneously.

Global constraints Finally, Equation 5.52 reports the power balance constraint for the commercial unit.

$$dP_{grid_{in}-c}(k) + dP_{grid_{ab}-c}(k)) + dP^{AC}_{load-c}(k) = 0 \quad for\, k = 1:96 \tag{5.52}$$

5.4.2 Aggregator

In the previous optimization, all the considered units were not interacting together and the algorithm was solved relatively to the single unit. Oppositely, in this new scenario the flexibility of each unit is mashed together by an aggregator which role is to find out the best way to exploit it in order to perform a specified task that depends on the considered scenario. However, the adopted aggregator model is the same for both of them and is depicted in Figure 5.26

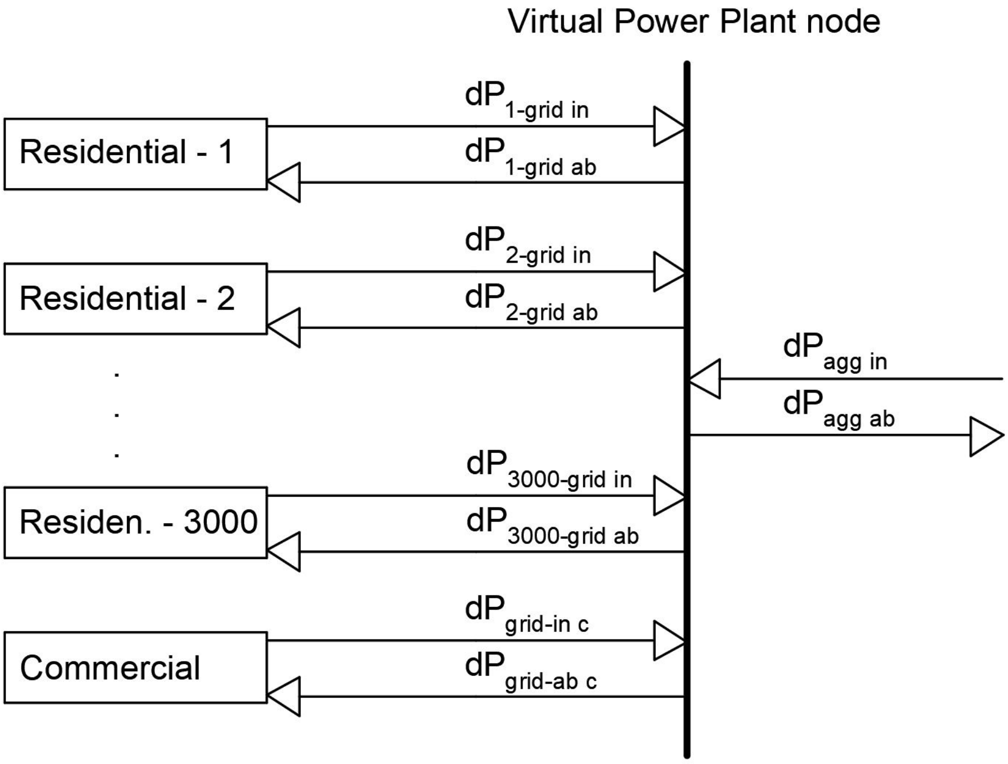


Figure 5.26: *Aggregator* model.

In the same way, the same power balance constraint characterizing both the analyzed situations can be represented exploiting Equation 5.53, in which the aggregator has to compensate the grid exchanges of both the residential and commercial units. These equation considers the sum of the power that each unit exchanges with the electrical grid. The aggregator role is to manage the units power flows at the common bus that, in this case, is representative of the virtual power plant. The energy exchanged by the virtual plant is identified as the energy exchanged by the aggregator. Particularly, according to the adopted constraints, it results that the sum of the injected power in the VPP node by all the units equals the absorbed power from the VPP node by the aggregator and viceversa.

$$\sum_{i=1}^{3000}(dP_{i-grid_{in}}(k)+dP_{i-grid_{ab}}(k))+dP_{grid_{in}-c}(k)+ \\ +dP_{grid_{ab}-c}(k)=-(dP_{agg_{in}}(k)+dP_{agg_{ab}}(k)) \quad for\, k=1:96 \tag{5.53}$$

where the variables $dP_{agg_{in}}(k)$ and $dP_{agg_{ab}}(k)$ are respectively the injected and the absorbed power variations with respect to the reference profile of the aggregator at time interval k.

Similarly, constraints that limit the power within the limits are reported in Equations 5.54 and 5.55, two binary variables have been introduced, therefore also Equation 5.56 is required that avoids the simultaneously absorption and injection of power, which would not be feasible. Regarding the aggregator power variation limits they have been chosen equal to $\Delta^{agg}_{max_{ab/in}} = \pm 20\,MW$.

$$0 \leq dP_{agg_{in}}(k) \leq \Delta^{agg}_{max_{in}} \cdot \alpha_{agg_{in}}(k) \quad for\,all\,k = 1:96 \tag{5.54}$$

$$\Delta^{agg}_{max_{ab}} \cdot \alpha_{agg_{ab}}(k) \leq dP_{agg_{ab}}(k) \leq 0 \quad for\,all\,k = 1:96 \tag{5.55}$$

$$\alpha_{agg_{ab}}(k) + \alpha_{agg_{in}}(k) \leq 1 \quad for\,all\,k = 1:96 \tag{5.56}$$

Also in this case it is necessary to introduce binary variables ($\alpha_{agg_{ab}}(k)$, $\alpha_{agg_{in}}(k)$) to avoid the simultaneously injection and absorption of power.

From now on, it is necessary to distinguish between the two presented cases, both of them considers an increasing offer to be submitted in the ancillary services market.

1. First scenario

   With reference to UVAM constraints, it has to be guaranteed that if a variation with respect to the baseline occurs, it has to be maintained at least for$\Delta_{min} = 4$ consecutive hours and has to be constant with respect to the baseline. To comply with them, in the first scenario a $\Delta_{min} = 4$ hours has been chosen. According to MB acceptance prices evaluation, optimization identifies which is the best time interval in which the constant variation has to be applied. A binary variable has been defined for every k-period, namely $\varphi(k)$, that identifies the occurrence of a variation with respect to the baseline. Once this variation occurs, it has to elapse at least for Δ_{min}; this can be imposed setting Equation 5.57, defining $i = \varphi(k) - \varphi(k-1)$, for $k = 2 :96 - \Delta_{min} + 1$.

$$\begin{gathered} \varphi(k*) \geq i \\ for l\,k* = k+1 : k + \Delta_{min} - 1 \end{gathered} \tag{5.57}$$

   Further, also the power variation has to be kept constant with respect to the baseline for the intervalΔ_{min}, this is imposed through Equation 5.58.

$$\begin{gathered} i \cdot M \leq dP_{agg_{in}}(k*) - dP_{agg_{in}}(k) \leq (1-i) \cdot M \\ for\,k = 1 : 96 - \Delta_{min} + 1\, for l\,k* = k+1 : k + \Delta_{min} - 1 \end{gathered} \tag{5.58}$$

   in which M has been chosen as an high value with respect to problem data so to have the equality ensured only when the binary parameter equals one; in this case M has been chosen equal to 1000. It is of paramount importance to realize that i is not a vector, but a parameter that changes every time interval.

To continue, it is important to point out the assumption relatively to aggregator market participation. In this scenario, the optimization do not ensure the aggregator to be accepted in the market, it only provides it with the offer that maximizes its revenues and the time interval in which it has to be submitted. For this reason, it has been assumed that aggregator cannot vary its baseline before knowing if it has been accepted in the market or not. To force this constraint, Equations 5.59 and Equation 5.60 have been introduced:

$$dP_{agg_{in}}(k) \leq \sum_{k=1}^{k} \varphi(k) \cdot M \tag{5.59}$$

$$dP_{agg_{ab}}(k) \geq -\sum_{k=1}^{k} \varphi(k) \cdot M \tag{5.60}$$

this implies that only when the binary value φ equals 1 for the first time a variation with respect to the baseline can occur; along with the previously mentioned constraints the desired result can be achieved. Parameter M has been chosen as an high value with respect to problem data, in this case it equals 1e6. Since the previously constraints do not impose that the variation length equals Δ_{min} but just that it results at least equal to Δ_{min}, Equation 5.61 has to be introduced.

$$\sum_{k=1}^{96} \varphi(k) = \Delta_{min} \tag{5.61}$$

Moreover, instead of allowing the variation to occur all day long, it is possible to limit the evaluation within a certain limit defined by time h_i and h_f in Equations 5.62 and 5.63.

$$\varphi(k) = 0 \quad for\, k = 1 : h_i - 1 \tag{5.62}$$

$$\varphi(k) = 0 \quad for\, k = h_f + 1 : 96 \tag{5.63}$$

In which h_i and h_f can be set in order to constrain the variation between a specified time interval. It is important to realize that the baseline, once the offer acceptance has been ensured by the market, can be varied in the periods coming after the dispatching order variation, according to baseline modification rules. This is pivotal when speaking about load shifting since, if a cycle has been shifted to respect dispatching orders, it still has to run after the dispatching order satisfaction. The baseline has to be modified with respect to the previously forwarded one that did not account for the shifted cycle. The just mentioned consideration, introduces an issue in the formulation of the objective function, this because just the baseline variation related to the ancillary services market has to be remunerated while, the others, has not. To avoid the creation of a bi-linear problem, this objective function may be written exploiting 2 new variables, namely $dP^1_{agg_{in}}(k)$ and $dP^2_{agg_{in}}(k)$. These are subject to constraints presented in Equations 5.64, 5.65 and 5.66. First two constraints allow to obtain a replica of vector $dP_{agg_{in}}(k)$ only outside the MB participation interval, while, inside, it results zero, this is represented by $dP^1_{agg_{in}}(k)$. The last one gives a vector that reports only the variation occurred during the MB market participation, represented by $dP^2_{agg_{in}}(k)$.

$$-\varphi(k)\cdot M \leq dP^1_{agg_{in}}(k) - dP_{agg_{in}}(k) \leq \varphi(k)\cdot M \quad for\, k = 1:96 \tag{5.64}$$

$$-(1-\varphi(k))\cdot M \leq dP^1_{agg_{in}}(k) \leq (1-\varphi(k))\cdot M \quad for\, k = 1:96 \tag{5.65}$$

$$dP^2_{agg_{in}}(k) = dP_{agg_{in}}(k) - dP^1_{agg_{in}}(k) \quad for\, k = 1:96 \tag{5.66}$$

This last vector is adopted in the objective function, presented in the next paragraph; M still represents an high value with respect to problem data, namely 1000.

2. Second scenario

   In this case, since no optimal time and quantity have to be computed, the required constraints have to account that before knowing of the acceptance or not of the offer, the baseline has to be respected; than, if accepted, dispatching order has to be respected and, after that, baseline can be modified. Therefore, Equation 5.67 and 5.68 avoid the variation of the baseline before the dispatching order notification, it has to be defined for each i-user

$$dP_{i-grid_{in}}(k) = 0 \quad for\, k = 1:GME_{start}-1 \tag{5.67}$$

$$dP_{i-grid_{ab}}(k) = 0 \quad for\, k = 1:GME_{start}-1 \tag{5.68}$$

The same has to be done for the aggregator, as shown in Equation 5.69 and 5.70

$$dP_{agg_{in}}(k) = 0 \quad for\, k = 1 : GME_{start} - 1 \tag{5.69}$$

$$dP_{agg_{ab}}(k) = 0 \quad for\, k = 1 : GME_{start} - 1 \tag{5.70}$$

Finally, the imposed variation has to be respected, and for this constraints Equation 5.71 is introduced.

$$dP_{agg_{in}}(k) = GME^{in}_{quantity} \quad for\, k = GME_{start} : GME_{end} \tag{5.71}$$

The quantity $GME_{start/end}$ and $GME^{in}_{quantity}$ are respectively the start, ending times and quantity of the dispatching order, clearly the quantity will be referred either to the an injection or absorbing offer.

5.4.3 Objective function

Also the objective function has to be written separately for the two considered problems, consequently:

1. First scenario

   The adopted objective function is represented in Equation 5.72 where OFF offers have been considered, it should be noticed that only some variations with respect to the baseline result remunerated. These are the ones offered and accepted in the MB market. Viceversa, the variations that occur after that the dispatching order has been accomplished are not considered. They are programmed by the aggregator in advance and are declared as baseline modification, thus not producing a profit on the MB market. For example, let's suppose that the aggregator is offering a power injection on the balancing market. If the offer results accepted, the aggregator will shift assets scheduling to respect the dispatching order and the units energy demands. This could implies a variation of the baseline also after the dispatching order is ended. This variation is not used for balancing market purposes, but only for satisfying the units energy demand and it will be programmed in advance as soon as the dispatching order is received by the aggregator:

$$min(-\sum_{k=1}^{96} C_{MB}(k) \cdot dP^2_{agg_{in}}(k)) \tag{5.72}$$

where the $C_{MB}(k)$ is the vector of OFF prices obtained by the market analysis. Particularly, the objective function will be run two times, the first considering summer prices, the second considering winter ones.

A point has to be clarified, looking at the objective function, it is possible to observe that no distinction between injected and absorbed power is necessary for what concerns the grid variables; this means that the represented model could have been implemented reducing the variable number. However, since different objective functions may be implemented keeping the same formulation model, with the goal of presenting as much as possible exploitable model, it has been decided to distinguish between power flow direction with reference to the grid, even if, in this formulation, it is not strictly necessary.

2. Second scenario

In this case there are no units for which a curve that relates power variation to a cost can be defined, for this reason it has been chosen to consider a fictitious cost (C) to be associated with the variation of the power profiles of the users and the commercial unit, both if power has been increased or decreased with respect to the reference curve. In this way, the objective function can be defined as presented in Equation 5.73, in which the goal is to minimize the cost respecting the notified dispatching order.

$$min(C \cdot \sum_{k=1}^{96}(\sum_{i=1}^{3000} dP_{i-grid_{in}}(k))) + K_C \cdot dP_{grid_{in}-c}(k))+ \quad (5.73)$$

$$-C \cdot (\sum_{k=1}^{96}(\sum_{i=1}^{3000} dP_{i-grid_{ab}}(k))) + K_C \cdot dP_{grid_{ab}-c}(k)) \quad (5.74)$$

the coefficient K_C is introduced in order to account for an incentive or a penalty term implied to the commercial unit participation; it has the dimensions of €/kW and it can be exploited to vary the participation of residential and commercial units during a dispatching order execution. Particularly it could be used in order to freeze the participation of the commercial unit if it is not strictly necessary; this can be done assigning to it a value which is higher than one. The same approach could be used if, further developing the presented algorithm, other unit typologies would be consider, creating in this way a hierarchical participation structure.

5.4.4 Results

5.4.4.1 Scenario 1

It has not been possible to evaluate 3000 residential units, since it would have required a too long computational time. To avoid this problem, an assumption has been made; instead of considering 3000 of different units, 30 units-type have been evaluated, than, results have been scaled to obtain 3000 units that include 100 units per type-profile. The considered profiles have been evaluated as follows:

1. 30% do not install neither ESS nor PV plant;
2. 20% install a PV plant but not an ESS;
3. 50% install both ESS and PV plant

Furthermore, scaling these profiles to match 3000 units, it has also been considered that, in a specific day, the percentage of users that do not allow completely the control of their devices is as follows, during summer:

1. 26% do not allow the control of the dish-washer;
2. 16% do not allow the control of the washing-machine;
3. 3% do not allow the control of neither dish-washer nor washing-machine;
4. 4 % do not allow the control of the air-conditioner.

while, during winter:

1. 27% do not allow the control of the dish-washer;
2. 13% do not allow the control of the washing-machine;
3. 8% do not allow the control of neither dish-washer nor washing-machine;

In the following some of the considered typical profiles and the results obtained from the simulation have been shown. They are reported considering a reference profile, which is representative of the historical one; a power variation profile, that considers the occurred variation due to MB participation and, finally, the modified profile which is the actual power profile followed by a unit if participates to the balancing market, it equals the sum of the previous two profiles.

In Figure 5.27, user-type 4 has been considered during summer period. As observable this user do not install neither PV and ESS. Flexibility is provided by the loads, in this example, the power variations show that dish-washer has been shifted, as it has been for the washing-machines. For what concerns the air-conditioner, its injection has been modulated. It is worth to remark that a positive variation for a load is representative of a decrease on the absorbed power, a negative one, on the opposite, identifies a power absorption increase. Finally, since in this very case the only slack-bus is the grid, it results trivial to realize how the power balance is ensured by it. A deeper analysis can be accomplished, concerning the reference power profile nothing the same guidelines adopted for the description of Figure 5.11 can be adopted, paying attention that, in this case, load absorption is represented as a negative power profile. With reference to the power profile variation, it is possible to appreciate how the DW has been shifted from 6.00 a.m to 5.00 p.m. The same occurred for the washing-machine, which cycle has been moved from 8.15 p.m to 10.00 p.m. Power variation are positive if, with respect to the reference profile, a power absorption decrease has occurred and viceversa. The same considerations on power increase and decrease can be carried out regarding the air-conditioner system, in this case it is possible to realize how a power modulation is carried out, increasing or decreasing the power absorption respecting the problem constraints without varying the total absorbed energy. In the modified profile it is possible to appreciate the resulting power curve, the load shifting and the modulation are clearly depicted. The presented analysis can be carried out also for the other examples reported in the following, since it would be exactly the same, it has not been considered useful to repeat it for every user. However, some additional considerations will be done in the following with reference to some of the presented power profiles.

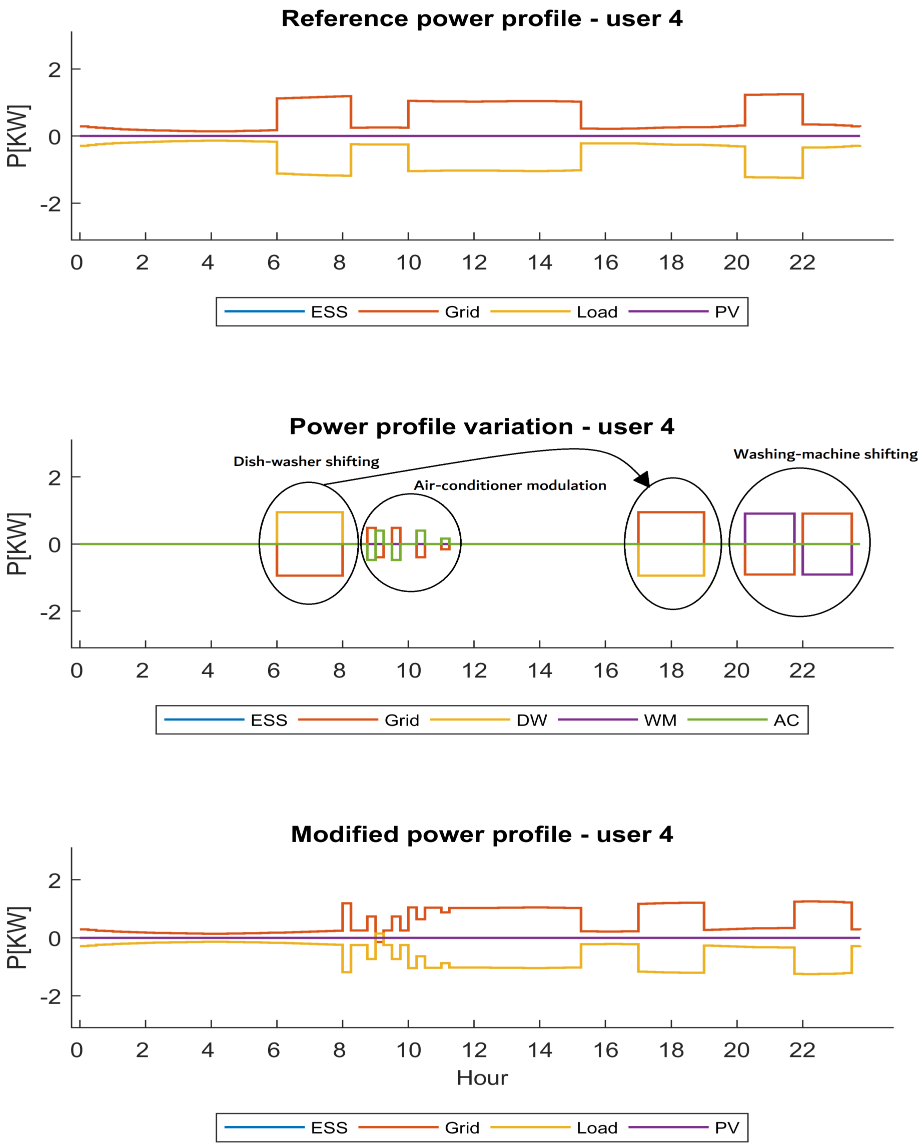


Figure 5.27: Summer - Power profiles of typical user 4

In Figure 5.28, typical profile of user 25 is depicted, in this case it is possible to observe that no PV or ESS are installed in this unit, moreover, this user do not allowed the control of the shiftable loads, for this reason, the only flexibility is provided by the air conditioner.

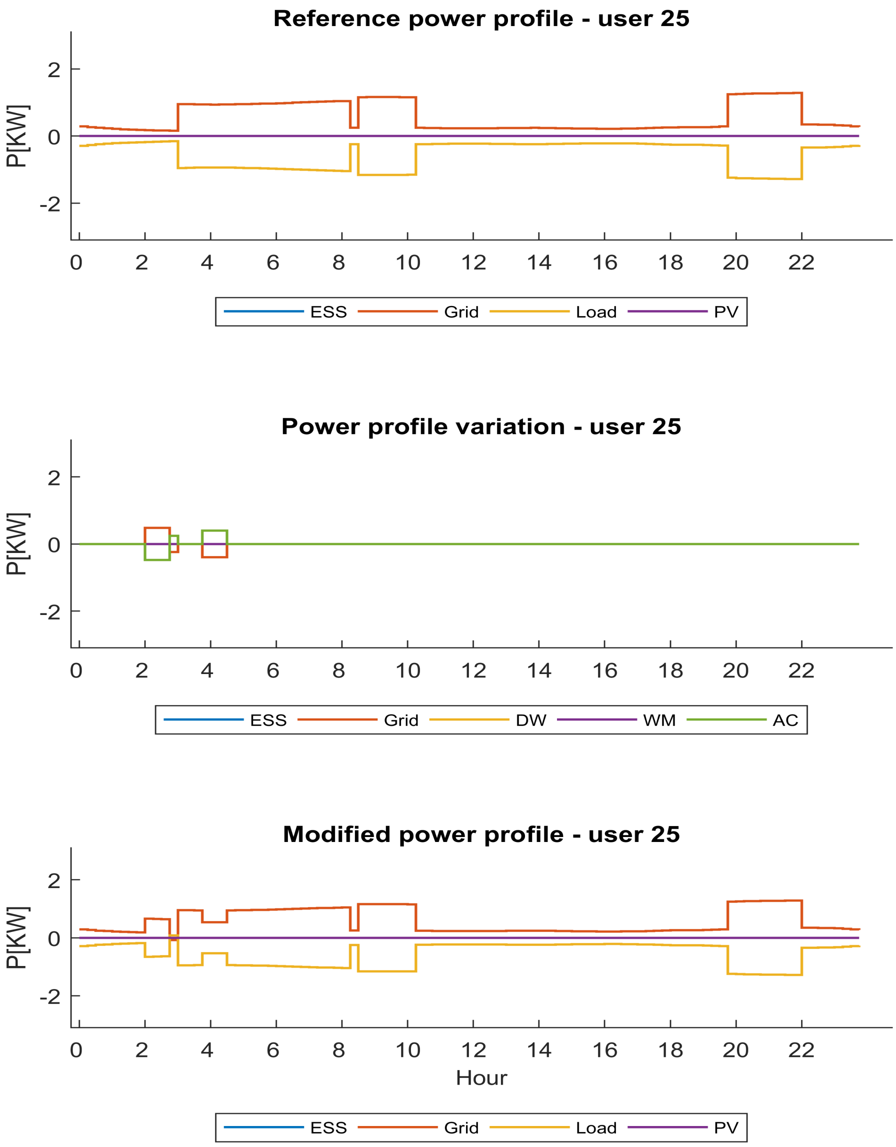


Figure 5.28: Summer - Power profiles of typical user 25

Considering another user typology, in Figure 5.29 power profiles of a unit that installs a PV system is represented. Particularly, it refers to typical profile 5, in this case both the washing-machine and the dish-washer are not available to the aggregator for flexibility evaluation.

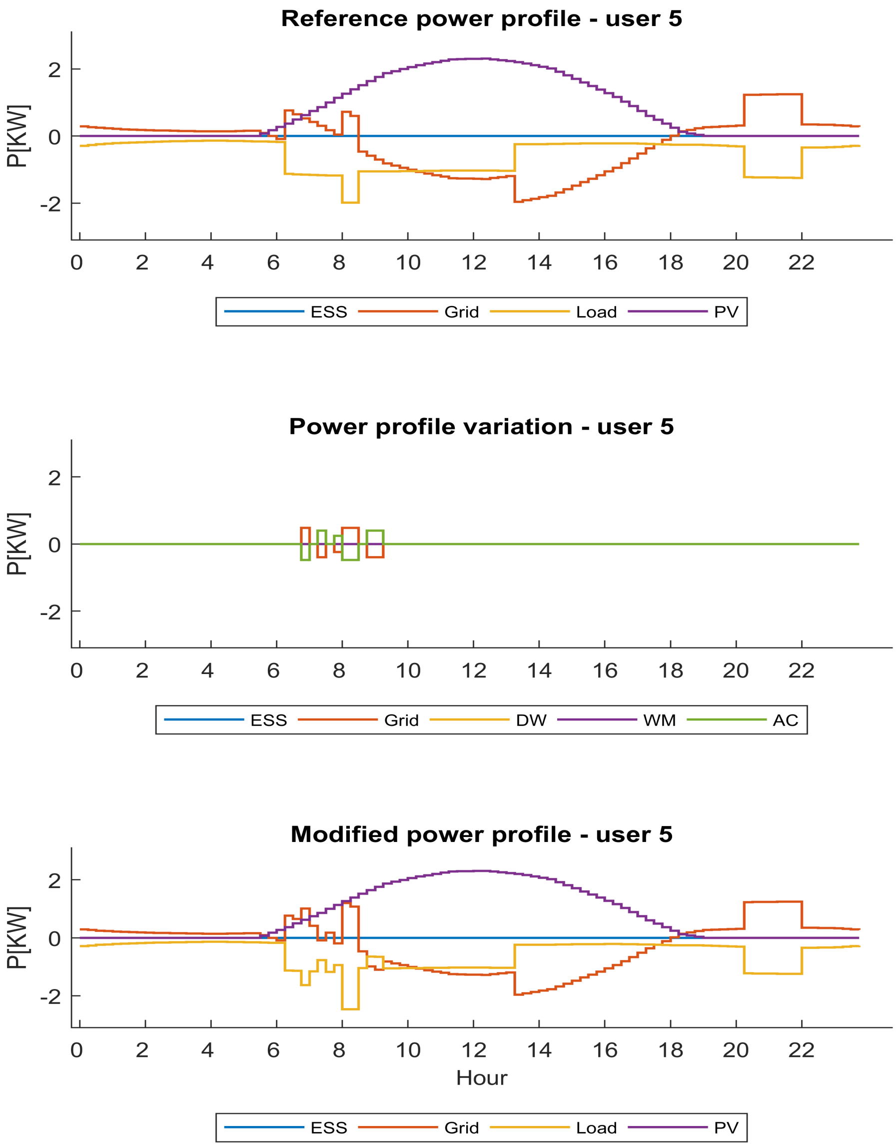


Figure 5.29: Summer - Power profiles of typical user 5

Finally, a user that provides the highest value of flexibility is considered, it installs a PV plant combined with a storage system, furthermore, all shiftable and modulable loads are available to provide flexibility to the aggregator. The considered profile is observable in Figure 5.30 It is immediately realizable that this unit has much higher capabilities than the previous presented ones in terms of power flexibility, this is clearly related with the installed storage system. Adopting the same procedure used for the analysis of user 4 profiles, also in this case it is possible to appreciate how load shifting and load modulation have been exploited, shifting the WM from 9.15 a.m to 11.00 a.m and the DW from 6.30 p.m to 8.45 p.m. Additionally, the storage flexibility has been exploited, varying the injection and absorption profile in different hours of the day. In this case, looking at the modified profile, due to the presence of many different controllable devices, the obtained profile could result difficult to analyze at a firs sight, however, it is possible to check that no-constraint violation occurs with reference to maximum power limits of different devices. If a single quarter of hour is analyzed, it is possible to verify the power balance, realizing that, for the evaluation of the power profile variation, the common node power flows have been used also for the energy storage system.

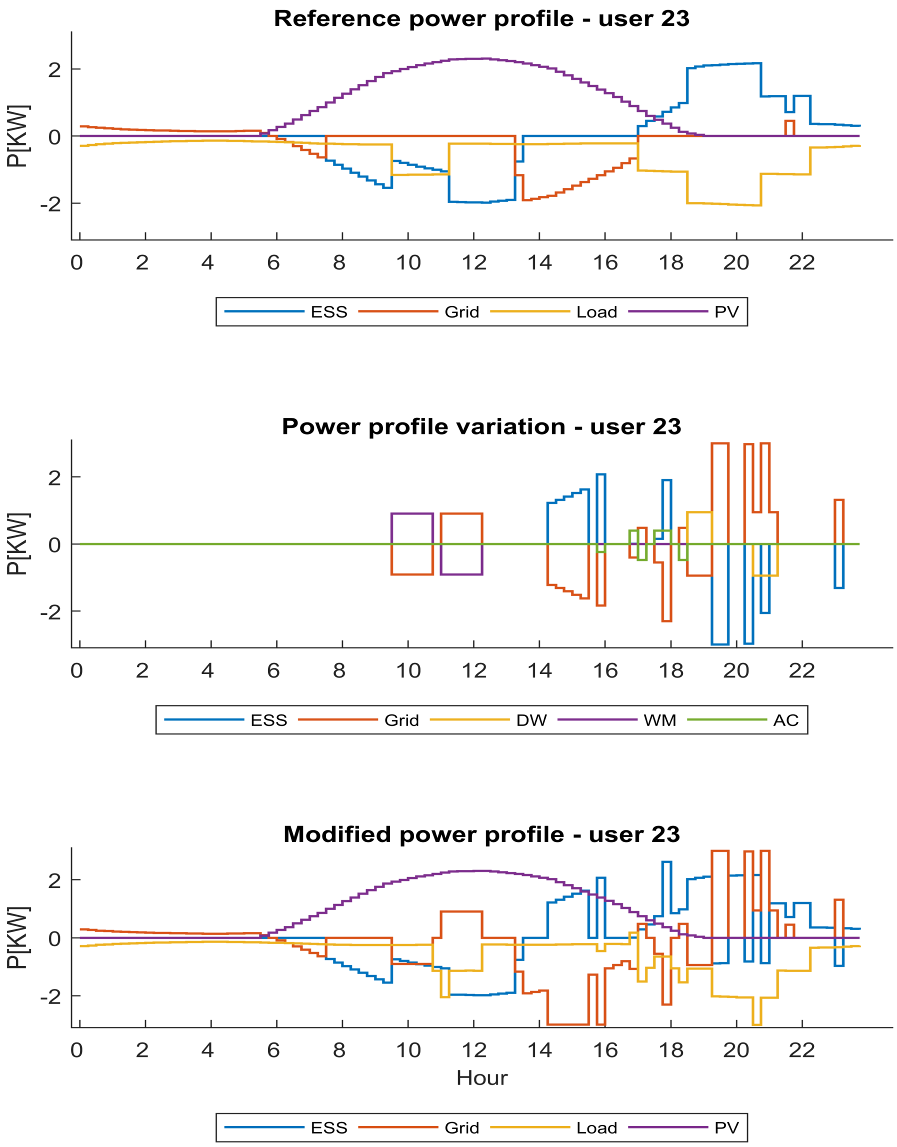


Figure 5.30: Summer - Power profiles of typical user 23

As far as the commercial unit is concerned, Figure 5.31 shows its power profile. It is worth noticing the flexibility provided by the air-conditioning system. The most relevant participation of the commercial unit in the optimization process occurs during the dispatching order execution. This seems reasonable because the air-conditioning system can be modulated without strictly constraints on cycle duration and continuity; for this reason, its flexibility can be used when it is required most.

Another proof of the high modulability provided by the commercial unit is given by the frequent power variations with respect to the reference profile that are exploited in order to respect the global power balance constraints of the optimization problem.

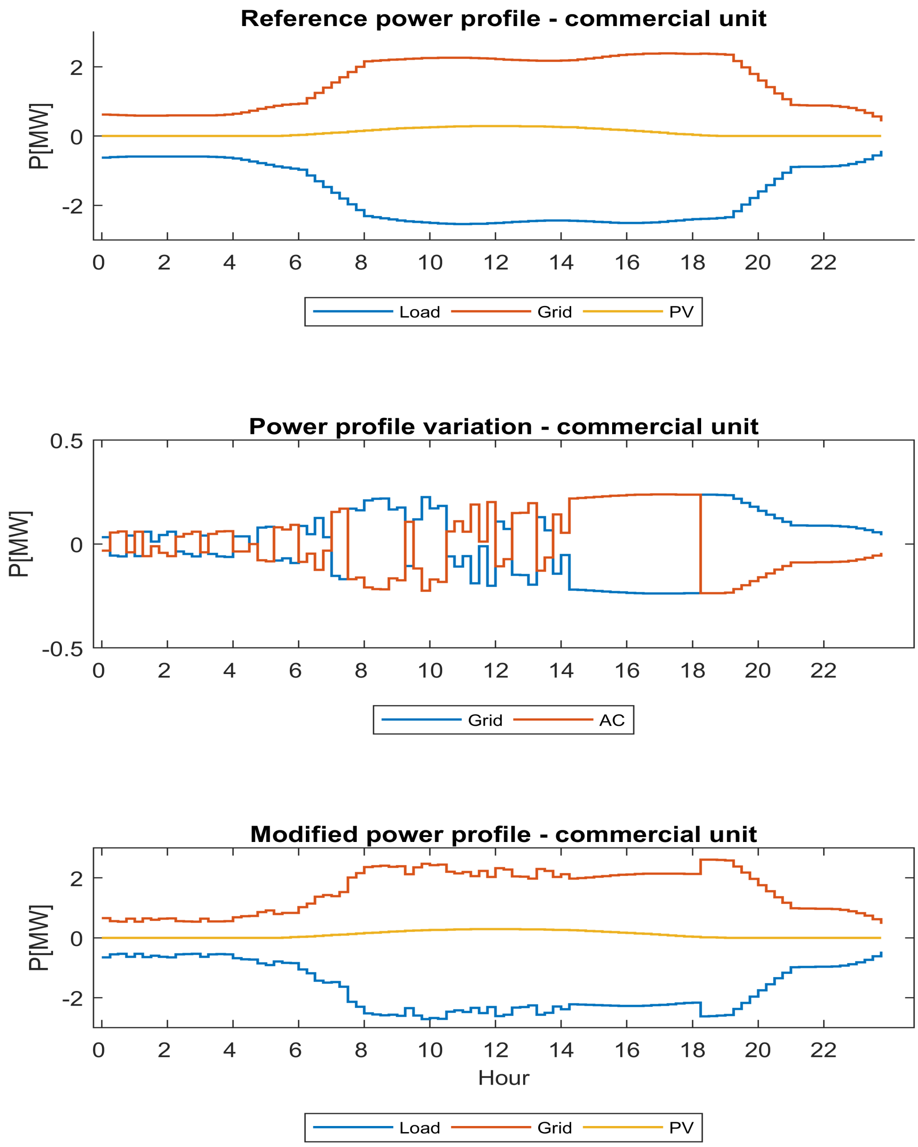


Figure 5.31: Summer - Power profiles of commercial unit

Finally, in Figure 5.32 the aggregator power profiles are illustrated. It is possible to observe how, with respect to the baseline, a constant power variation of almost 2 MW is provided from 2.30 p.m to 6.30 p.m. Before the dispatching order execution, no baseline variation occurs as required by the problem formulation. Furthermore, the achieved variation seems to be a reasonable value considering the studied aggregate. In fact, with a conservative assumption, considering a set of 3000 users and that the 80% of them participate to the variation it results that 2400 users effectively participate to the dispatching order execution. The flexibility that each user can provide is estimated of 800 W for a 4 hours interval. Globally, a 4 hours power variation of 1.9 MW is achievable by the aggregator exploiting only the residential units. Additionally, the power variation of the commercial unit has to be accounted for and it equals almost 200 kW. Therefore, a variation of almost 2 MW seems reasonable and can be considered as a correct result.

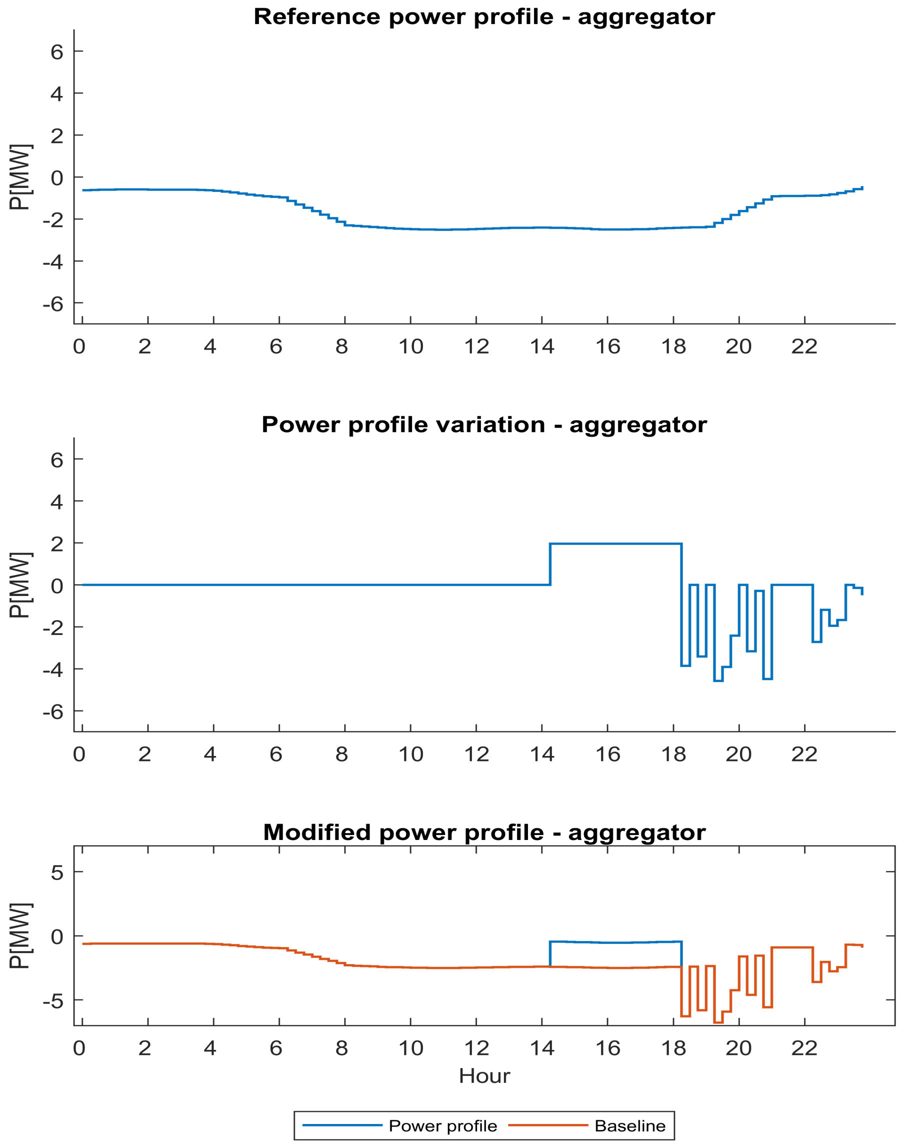


Figure 5.32: Summer - Aggregator power profiles

Now, as done for the summer profiles, also the winter ones have been considered. It is clear that the available flexibility would be lower since no air-conditioning systems have been considered. In Figure 5.33 a representative power profile of a user which allows the maximum flexibility is illustrated.

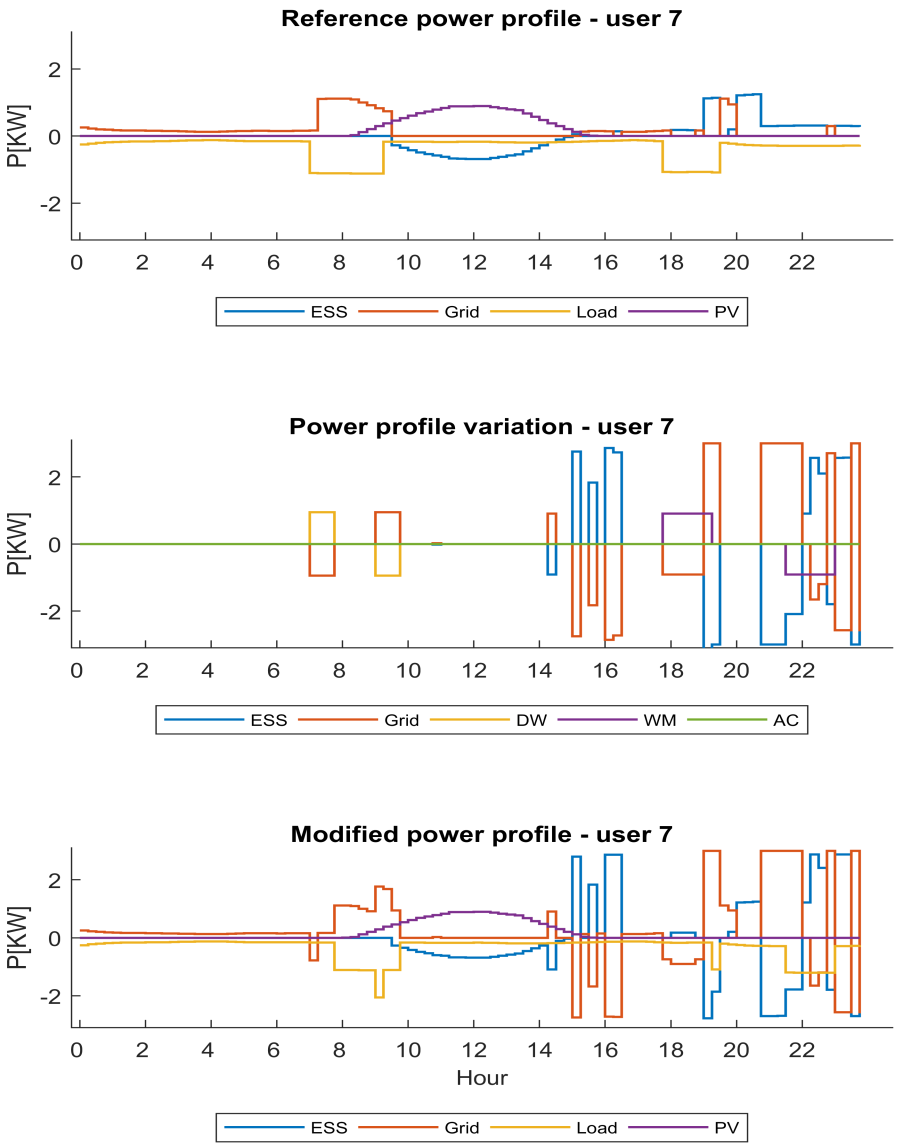
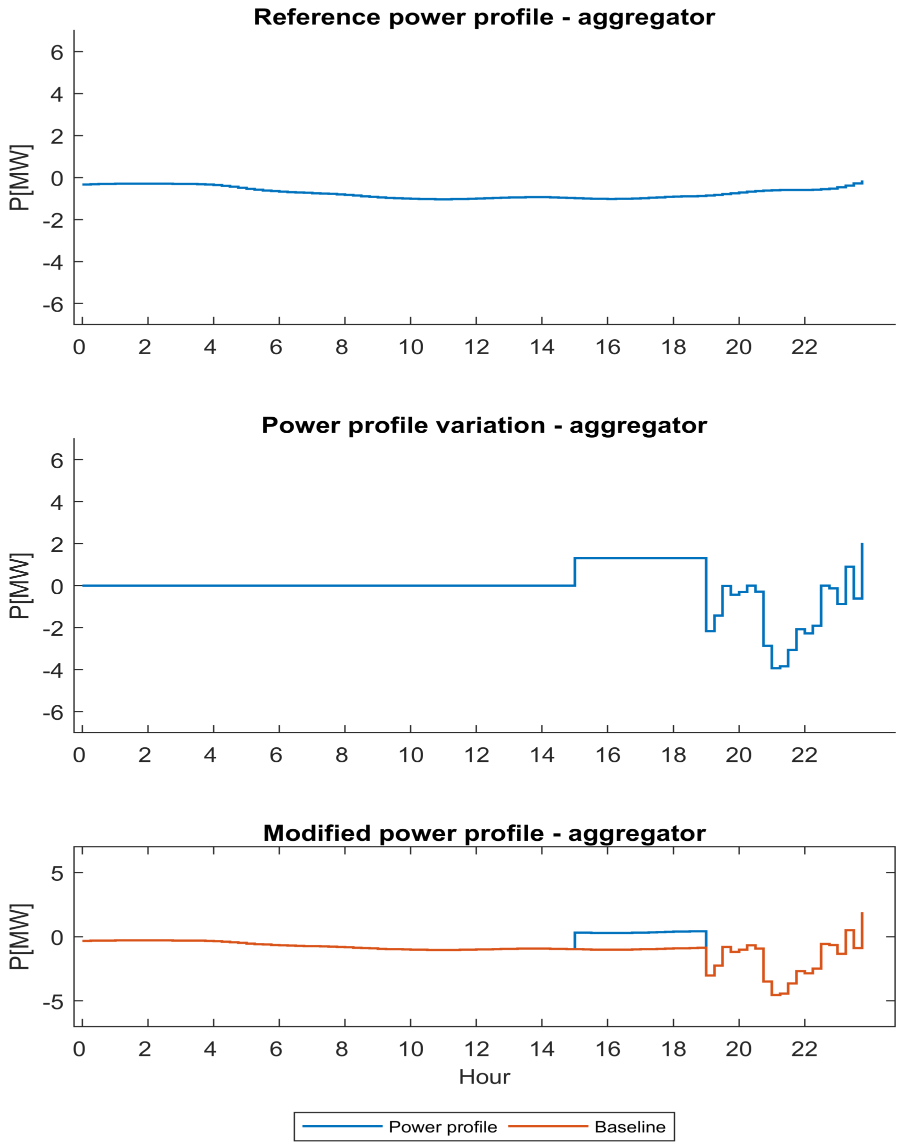


Figure 5.33: Winter - Power profiles of typical user 7

Concerning the commercial unit, since the only provided flexibility is related with AC system, that in this season is no longer present, it is not useful to report its power profiles. On the other hand, aggregator power profiles are reported in Figure 5.34. The provided flexibility is much lower than the previous case, it has been provided from 3.15 p.m to 7.15 p.m and the power variation equals almost 1.3 MW. This result is representative of the high importance covered by the air conditioning systems in providing power flexibility to an aggregate. Particularly, apart from the modulation offered during the dispatching order execution, commercial air-conditioning system has been effectively exploited, during summer season, to compensate the power variations of the residential units occurring before the confirmation of the dispatching order. If no commercial air-conditioning system is installed, this action can no longer be accomplished and the flexibility of the whole aggregate is strongly reduced.



one

Figure 5.34: Winter - Aggregator power profiles

Facing the problem from an economical point of view, different strategies can be considered regarding the remuneration methodology. A first approach could be to redistribute the aggregator incomes among all the users that have provided available flexibility. On the other hand, remuneration could be reserved only for the users whose flexibility has been actually exploited for ancillary services market participation. Furthermore, different appliances and devices, which allow to be controlled, could be differently remunerated depending on their modulability. For example, a storage is much more flexible than a shiftable load, for that reason it could have sense, from an economical point of view, to assign it an higher weight.

Considering the just presented scenario, it is possible to estimate the total incomes in a year operation, as shown in Equation 5.76, considering the summer (S) and winter (W) profiles applied for half of the year each.

$$T_{incomes} = a.p \cdot \frac{W_{incomes_{day}} + S_{incomes_{day}}}{2} \cdot 365 = \tag{5.75}$$

$$= 0.9 \cdot \frac{385\,€/\text{day} + 565\,€/\text{day}}{2} \cdot 365 = 156\,\frac{k€}{year} \tag{5.76}$$

Coefficient $a.p$ is representative of the acceptance probability, that is related with the prices considered for the income evaluation. In this first case it has been chosen equal to 0.9. It seems reasonable to consider that these incomes would be split between the aggregator and its managed units. A coefficient of 0.6 has been therefore assigned to the aggregator ($A_{incomes}$), while the remaining part is assigned to the units ($U_{incomes}$). It results:

- $A_{incomes} = T_{incomes} \cdot 0.6 = 93623\,€/\text{year}$
- $U_{incomes} = T_{incomes} \cdot 0.4 = 62415\,€/\text{year}$

The total incomes have now to be redistributed among the different units. Since it is not possible to daily define which would be the units that effectively contribute to the dispatching order execution, it has no sense to compute unit by unit which would be the amount of the remuneration. In fact, this remuneration changes day by day depending on the availability of devices flexibility which is strictly depending on user preferences. For this reason, in order to account for a participation factor, the number of total flexible loads or devices that actively participate during the dispatching order execution has been taken into consideration within the simulated day. Moreover, under the same considerations, the same economical weight has been assigned to each device. Participation factor ($p.f$) has been computed and considered representative of the average daily participation units among which the daily remuneration would be distributed. During summer it results of 84% while, during winter, this percentage decreases to 76%. For what concerns the commercial unit, the participation factor has been considered equal to 100%, identifying that the unit is effectively used every day. Moreover, since the power modulation level is almost 100 times higher with respect to the one provided by the residential units, it has been considered that the commercial unit remuneration equals that of 100 residential ones. Therefore, a per-unit income can be evaluated, it equals the residential unit income and, if multiplied by 100, it equals the commercial unit one. Of course, during winter, the commercial unit is no longer present, for this reason it has been differed between a summer and a winter case, Equations 5.78 and 5.77 report the per-unit incomes:

$$P.U_{incomes_{summer}} = \frac{S_{incomes_{day}}}{3000 \cdot p.f + 100} = 0.22\,€/day \tag{5.77}$$

$$P.U_{incomes_{winter}} = \frac{W_{incomes_{day}}}{3000 \cdot p.f} = 0.17\,€/day \tag{5.78}$$

To retrieve which is the average remuneration of each unit in one year, considering every unit characterized by the same probability of being effectively exploited for balancing market purposes, Equations 5.80 and 5.79 report the residential and commercial yearly summer incomes.

$$R_{incomes_{summer}} = a.p \cdot \frac{365}{2} \cdot P.U_{incomes_{summer}} \cdot p.f = 30.3\,€/\text{year} \tag{5.79}$$

$$C_{incomes_{summer}} = a.p \cdot \frac{365}{2} \cdot P.U_{incomes_{summer}} \cdot 100 = 3614\,€/\text{year} \tag{5.80}$$

In the same way, considering Winter period, Equations 5.82 and 5.81 are reported.

$$R_{incomes_{winter}} = a.p \cdot \frac{365}{2} \cdot P.U_{incomes_{winter}} \cdot p.f = 21.2\,€/\text{year} \tag{5.81}$$

$$C_{incomes_{winter}} = 0\,€ \tag{5.82}$$

Combining winter and summer incomes, the yearly achievable earnings from a residential and a commercial unit can be estimated, they result equal to $R_{incomes} = 51.5\,€/\text{year}$ and $C_{incomes} = 3614\,€/\text{year}$. These results will be discussed in the final considerations, in this section, instead, it is pointed out how, for a residential user, the achievable income due to the aggregate participation can be estimated as almost the 6% of the average annual electricity bill.

It is interesting to analyze which would have been the obtained incomes considering a lower acceptance probability, for this reason, different simulations have been considered. In Figure 5.35, 5.36 and 5.37 the winter and summer profiles of acceptance probability prices are illustrated.

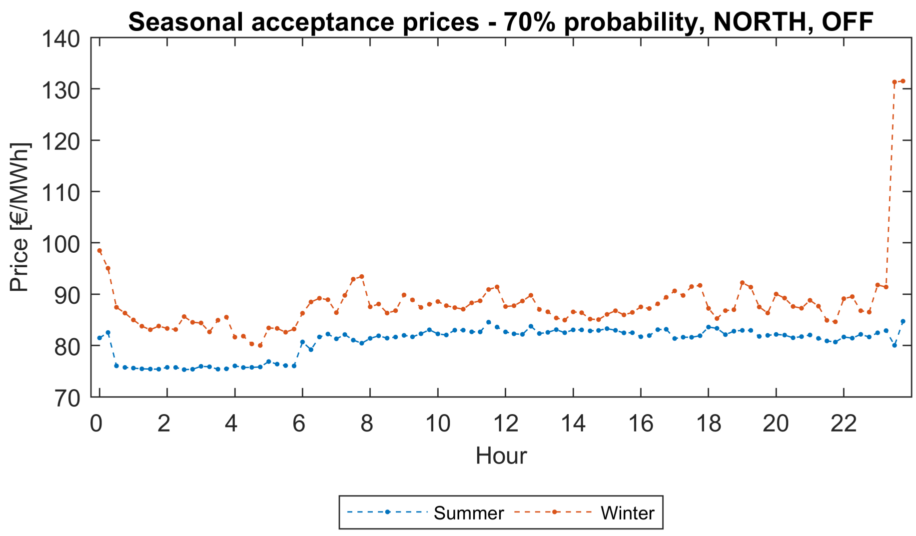


Figure 5.35: 70% acceptance probability prices

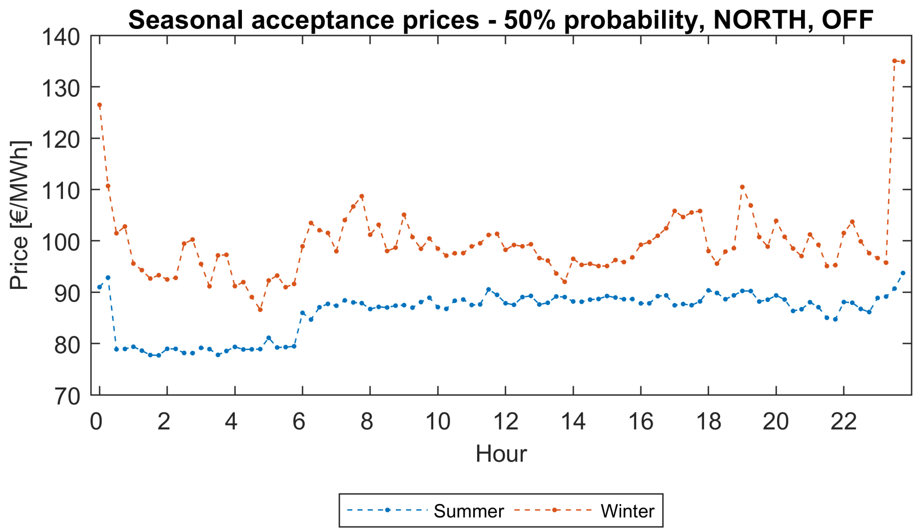


Figure 5.36: 50% acceptance probability prices

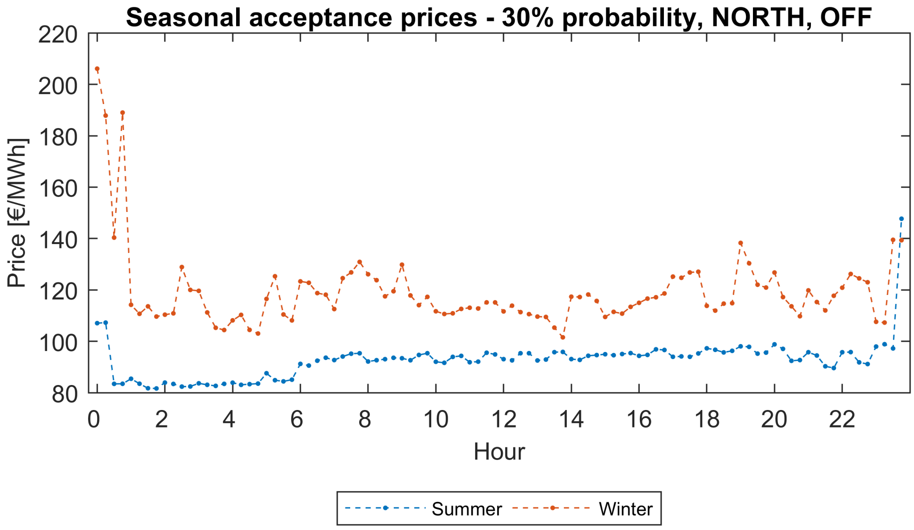


Figure 5.37: 30% acceptance probability prices

According to these the same variation previously analyzed has been economically evaluated, following the same methodology Table 5.3 has been obtained.

	Total incomes k€/year
90%	156
70%	146
50%	115
30%	83

Table 5.3: Economical comparison among different MB prices

Under the considered assumptions, it is not worth to increase the bid prices, this because the decrease of the acceptance probability is higher than incomes increase in case of acceptance.

5.4.4.2 Scenario 2

In this case scenario, an higher number of user type-profiles could have been introduced in the MATLAB simulation, this because of the easier problem formulation. However, since 30 is already a quite representative number, it has been kept. On the other hand, different evaluation with respect to the previous case have been carried out. Particularly, it has been possible to analyze if a certain variation, specified by a power quantity and a time interval, could have been faced with the considered aggregate. Further more, different participation coefficients K_C have been experimented, comparing the different responses of the system to the same specified variation. For instance, in Figure 5.38 the aggregator power profiles after a balancing market participation are reported. The participation parameter has been chosen equal to 1 €/kW, this means that no incentive or penalty has been assigned to the commercial unit. As observable, injection increase of 1 MW required from 2.45p.m to 6.45p.m is correctly dispatched.

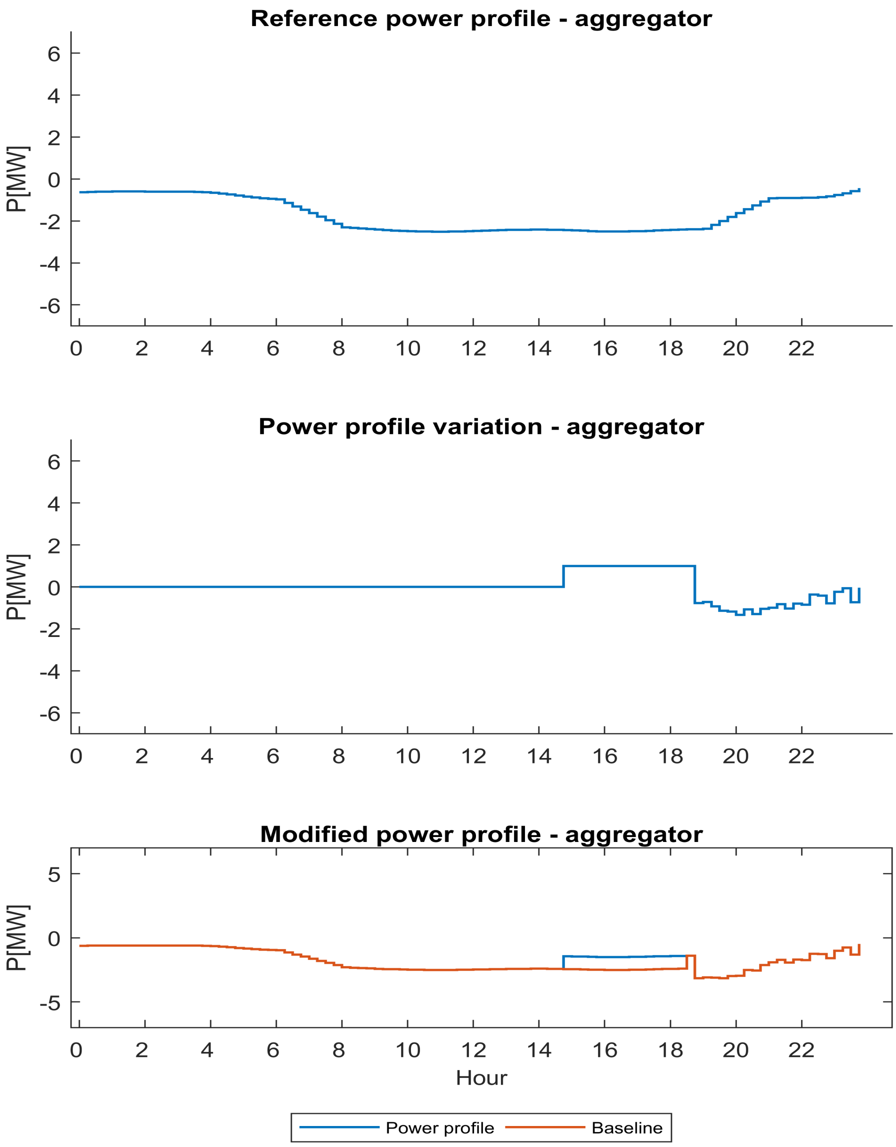


Figure 5.38: Summer - Aggregator power profiles

Focusing on the users-typo 19 it is characterized by the power profiles depicted in Figure 5.39. Load flexibility is deeply exploited since both DW and WM cycles are shifted in time.

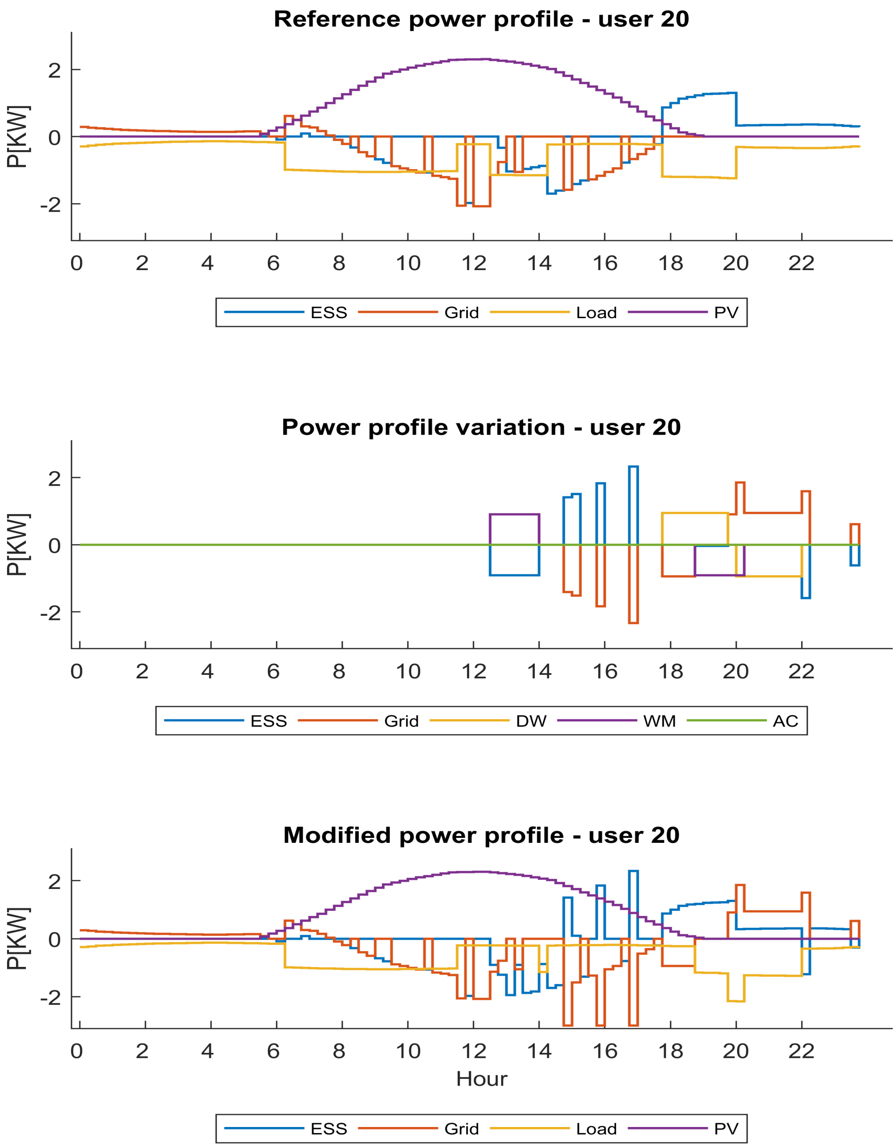


Figure 5.39: Summer - Power profiles of user 19

Looking at the commercial unit power profiles, they are reported in Figure 5.40. Clearly, also the flexibility associated with the unit air-conditioning system has been exploited.

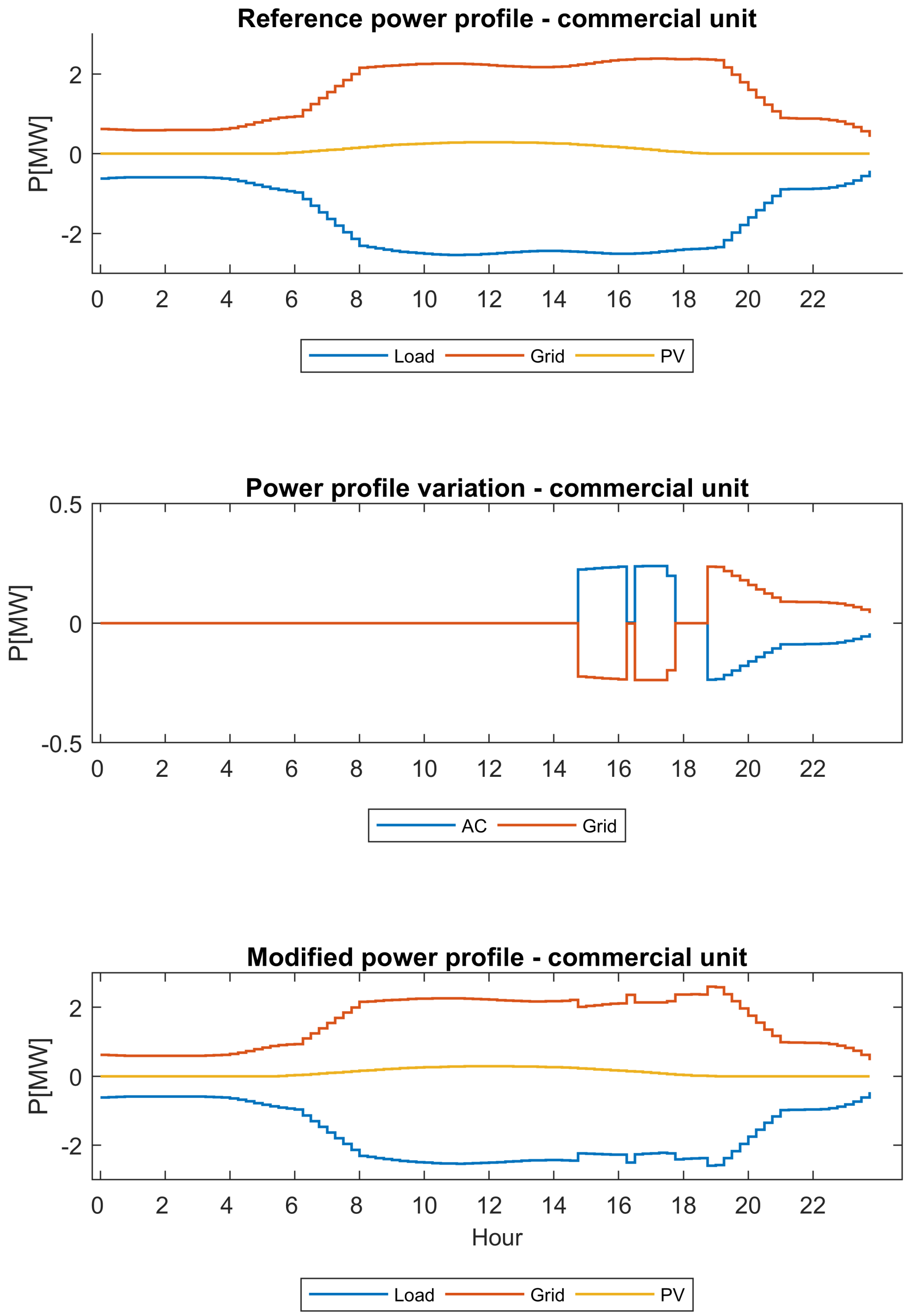


Figure 5.40: Summer - commercial power profiles

Another comparison is proposed considering a different participation factor, this time higher than 1 €/kWh. Results are depicted in Figure 5.41 with reference to the aggregator, than in Figure 5.42 and Figure 5.43 the power profiles of the commercial unit and of user-type 19 are illustrated.

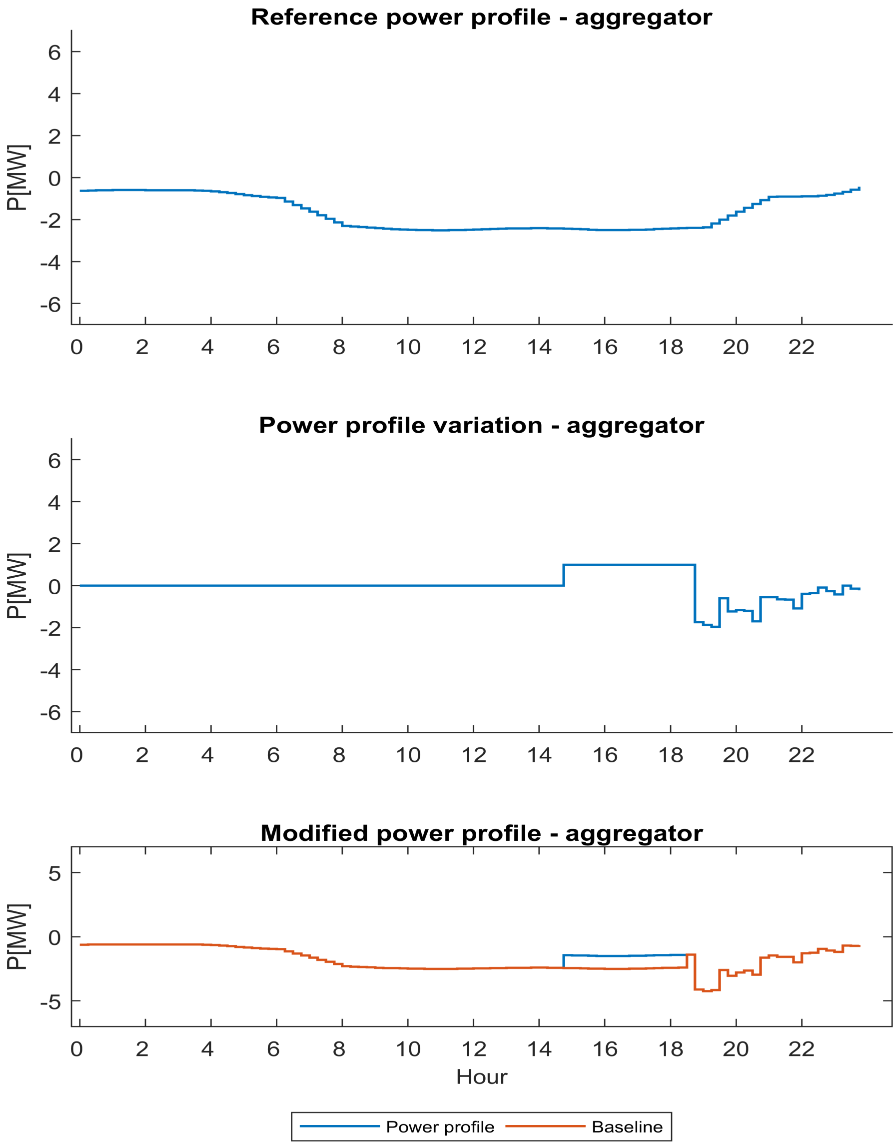


Figure 5.41: Summer - aggregator power profiles

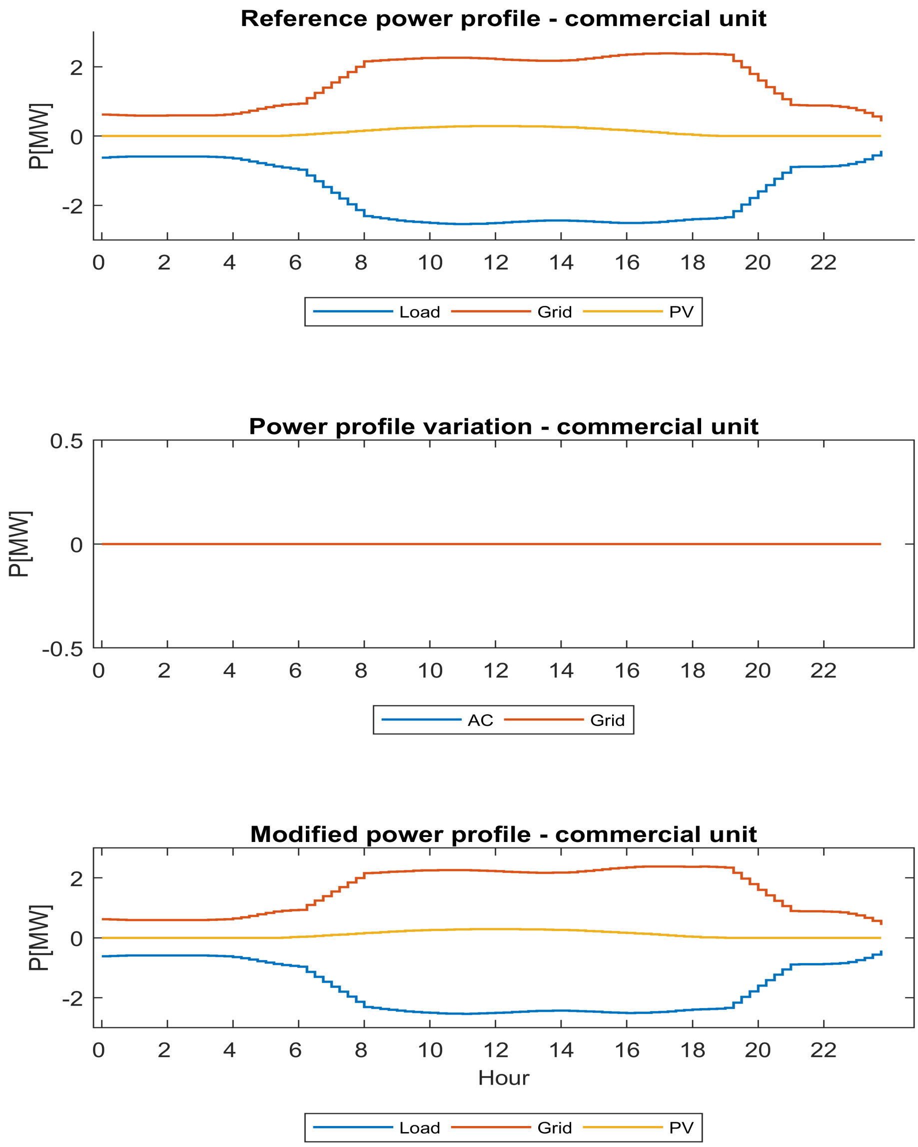


Figure 5.42: Summer - commercial power profiles

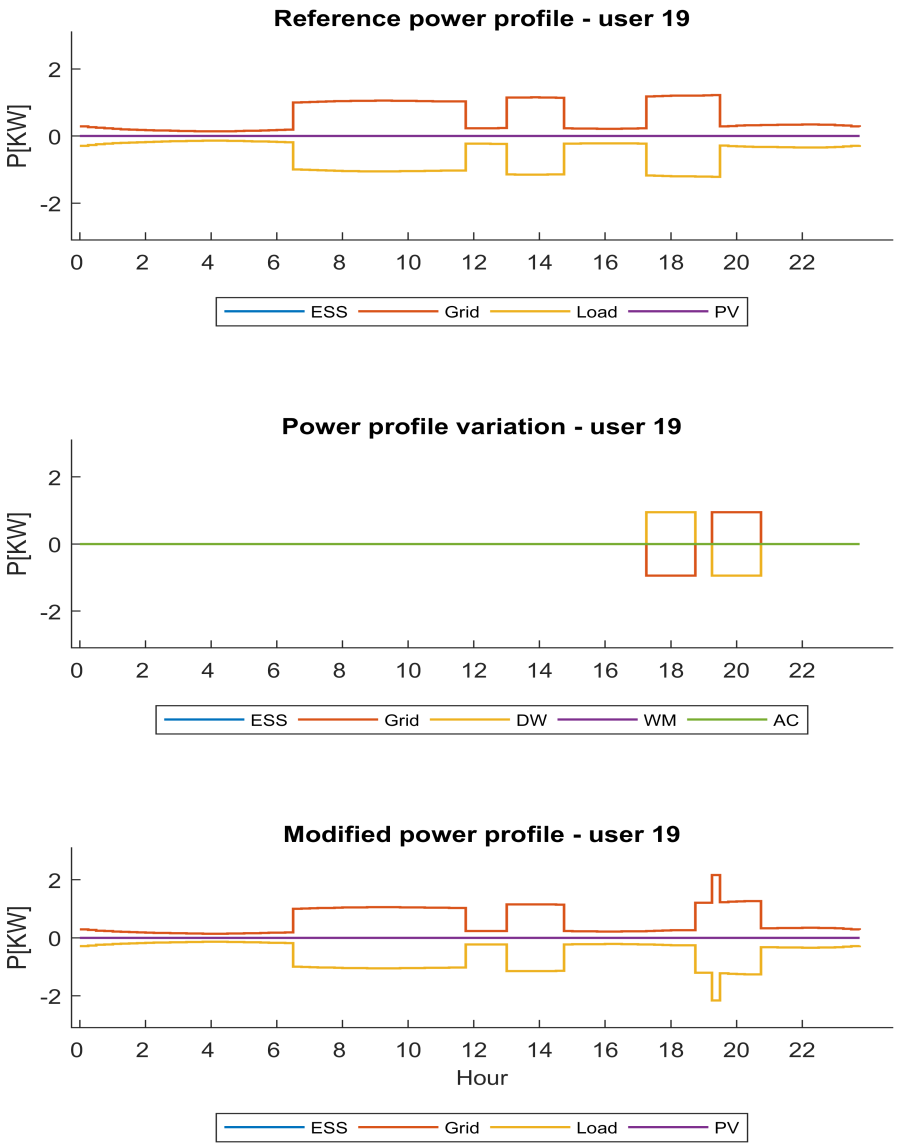


Figure 5.43: Summer - power profiles user 19

It is possible to realize that user-type 19 still participates to the market, however, commercial unit has no active role in the provided dispatching service, this because the 1 MW variation could be faced entirely by residential units. On the other hand, if an higher variation, for example equal to 1.9 MW is considered, even if the penalty factor is higher than 1, the commercial unit flexibility is still exploited. If not, the aggregate would not be able to face the required power variation. With respect to this last scenario, power profiles of aggregator, commercial unit and user-type 19 are respectively reported in Figures 5.44, 5.45, 5.46.

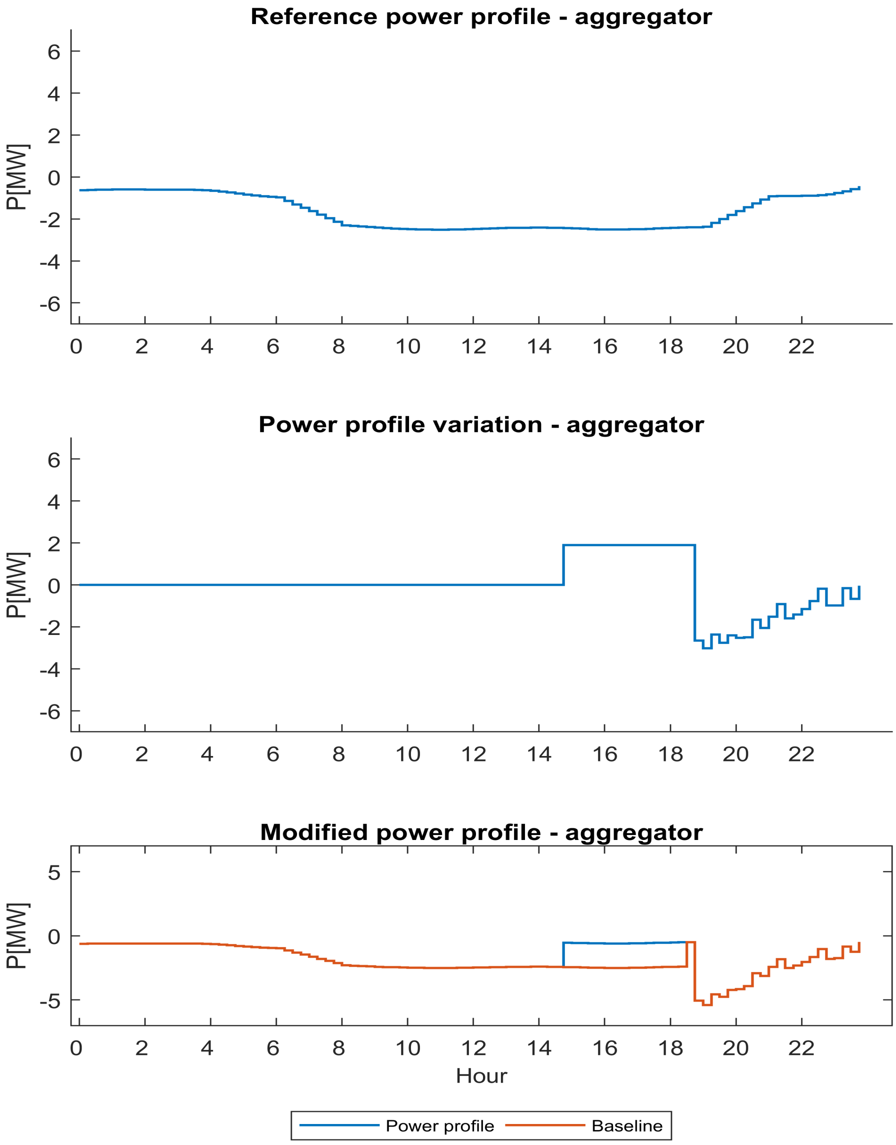


Figure 5.44: Summer - aggregator power profiles

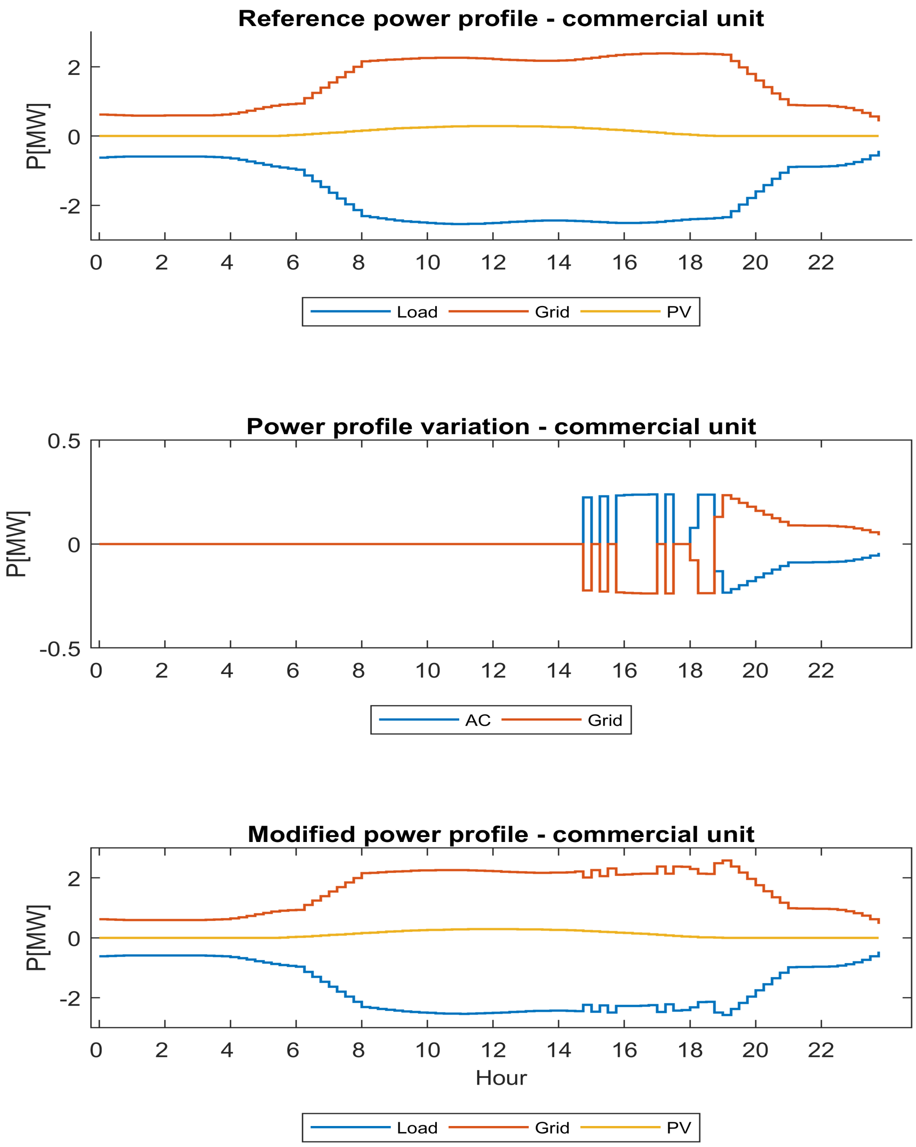


Figure 5.45: Summer - commercial power profiles

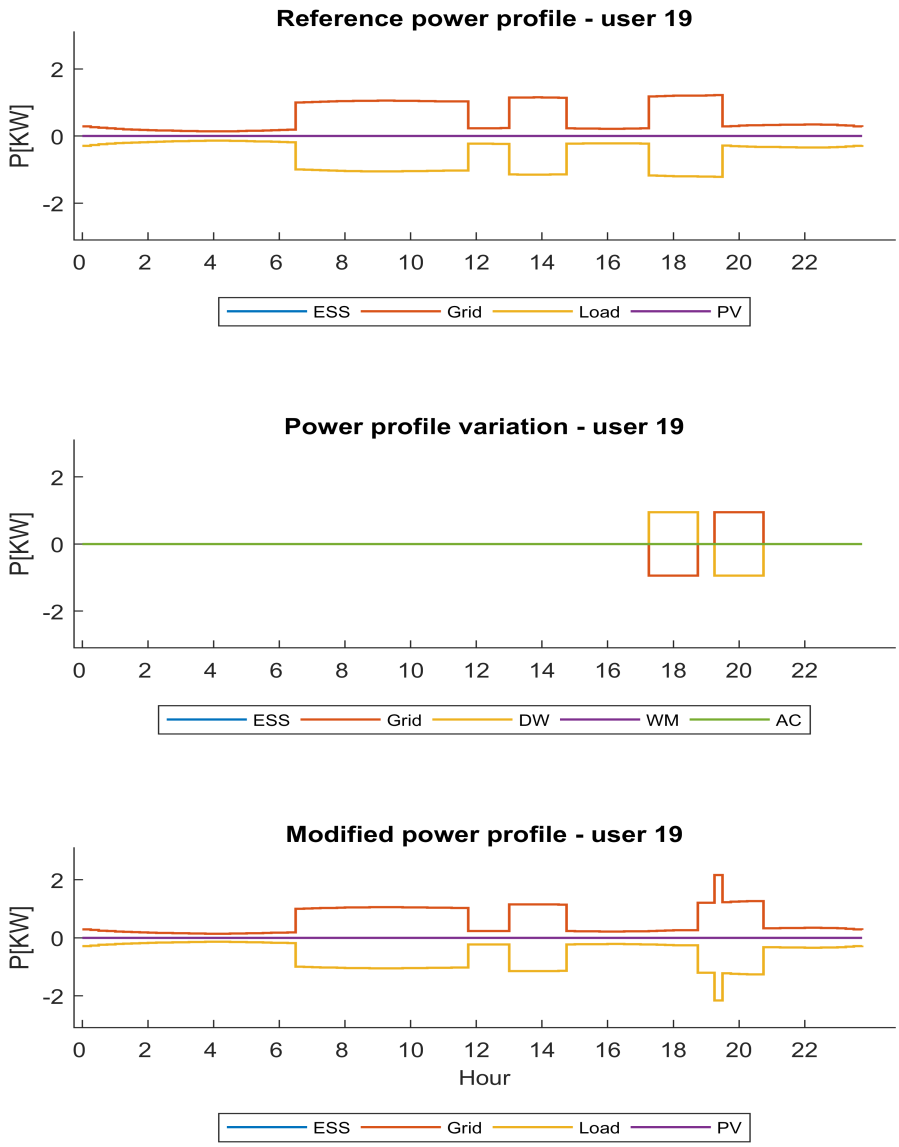


Figure 5.46: Summer - power profiles user 19

5.4.4.3 Scenario 3

Speaking about optimization algorithms, the ones developed for the resolution of Scenario 1 and Scenario 2 belong to the class of centralized ones. This name suggests how these kind of algorithms are solved by a unique computational unit. It is clear that all the information and problem constraints have to be handled by this unit that, consequently, has to be characterized by an high computational power. Even though, many problems are described by a very high number of variables and equation, this lead, also adopting high performance units, to unacceptable computational times. In fact, practical aspects often require the algorithm resolution to be completed within defined times. If this is not respected, the algorithm would result useless from a practical point of view. Examples of these problems are perfectly given by the ones considered in this work: an aggregator willing to achieve economical incomes exploiting DER has to be able to manage all their variables quickly, taking into account both technical constraints and economical dynamics describing the electricity market. Therefore, even if this thesis deals with academic case studies, it has been considered useful to briefly report the achievable advantages by adopting the so called *distributed optimization algorithms.* They allow a problem to be solved by many computational units. The advantages are that the units are not required to be high performance one, this because each unit would have to solve a small problem compared to the original one. To provide an example, instead of letting the aggregator to mange all the unit constraints, it could be possible to let him handle only the constraints relative to its power limitations and balances. On the other hand, each unit would solve an optimization problem considering just its own system constraints (ESS, load shifting, load curtailment, power balance and generally all the ones related with the unit appliances and grid). Resolution of this kind of problem requires an iterative process but, thanks to the small problems that have to be solved by each unit and to the fact that problems resolution could occur in parallel, this is convenient compared to the resolution of centralized problems. However, this methods allow to obtain just approximations of the problem exact solution, since the problem decomposition may led to loss of information. In any case, as explained in many different papers, as the [6] or [5], they are still able to provide enough accurate solutions.

5.4.5 Final considerations

This chapter explored two different scenarios analyzing the considered aggregate under two different points of view. The first one tries to study the problem from an economical horizon. The second one presents different possible solutions in which a required power variation could be realized, highlighting the different contributes achievable by residential and commercial units. Regarding the economical evaluation, the obtained results led to yearly incomes of 51.5 € and 3614 € respectively for residential and commercial unit. It is fundamental to realize that these results have not a general validity since they have been obtained under particularly hypothesis. First of all, focusing on the considered flexibility, it is important to realize how it results limited with respect to the one that could have been considered. To sustain this, it is sufficient to realize how, during winter season, the available flexibility is dramatically reduced since no heat system has been introduced. In fact, this would have led to an increase of the available flexibility since, as occurs for summer period, unity thermal inertia could be exploited. Additionally, more and more importance is covered by the so called CHP systems, thanks to which it could be possible to combine heat and power production and, therefore, generate flexibility that could be exploited in the electricity market. Speaking about the amount of considered units, it is important to recall that, due to computational limits, 30 user-type have been considered and then re-scaled. However, the achievable synergies are those related to 30 users that, instead, could have been incremented considering an higher amount of them. Finally, it can not be forgotten the vehicle to grid technology which is becoming an interesting matter for many companies in the energy sector. Moving from technical to economical considered assumptions, this thesis focuses on providing balancing market services, disregarding others that could be considered in further develops of these work. Additionally, recalling the UVAM forward ancillary services market, it is possible to realize, looking at the simulated dispatching orders, how the minimum requirements settled in order to gain the fix remuneration of 30000 €/MW/$year$ have been respected both during summer and winter seasons. Clearly, to be awarded of this sum, the variation has to be guaranteed for a certain amount of days, as reported in the previous chapters. In any case, it is reasonable to consider that the unit will be able to do that because, looking at the participation coefficients, it can be seen that not the entire set of users is participating to cover the dispatching order in the simulated day; moreover, the achieved power variations are higher than the minimum one required by TERNA, which equals 1MW. Finally, as reported in [17], the MSD market trend is constantly increasing. All the cited technical and economical aspects are clearly affecting in a positive way the considered economical analysis. Last but not least, with reference to the second scenario, the economical evaluation has not been taken into account, while the results have highlighted which are the actual capabilities of the residential users, without considering the commercial one. Only a particular scenario has been evaluated, a full evaluation would have been peformed focusing on different time periods, power variations and elapsed times.

Conclusions

This final dissertation has faced the current topic of dispatching services market evolution. In particular, the Italian scenario has been considered, reporting the actual regulatory frame highlighting the latest and more meaningful changes that have been implemented with respect to the traditional market structure. New concepts and definitions spreading in the electricity sector have been emphasized, introducing pilot projects that develop and promote them. Deepening on the Italian scenario and relative enabled projects has been accomplished, recognizing its technological and regulatory backwardness with respect to the most advanced countries in the world. Therefore, a step-forward has been done, analysing the potential of the distributed energy resources if considered in an aggregated form, especially exploiting residential appliances that reserve good properties to exploit for these applications. In this regard, a market-analysis tool has been implemented adopting MATLAB software, which has allowed to study the balancing market, handling accepted offers during 2017 to find out the relation between the offer price and its acceptance probability. After this preliminary evaluation, a hypothetical aggregate has been considered. This aggregate is constituted by 3000 residential units and a commercial one; these units can provide power flexibility thanks to load-shifting, load-modulation and smart energy storage systems management. Market analysis results and unit flexibility have been used as input for two different optimization algorithms, also developed with MATLAB. The first one maximizes the incomes that can be achieved by the aggregator on the balancing market. In details, according to the results obtained from the market analysis and to other specific problem constraints, it will define the bidding power quantity, the bidding time and the scheduling of the flexible devices. The second one, instead, focuses on minimizing the costs in order to respect a predefined dispatching order, pointing out the different flexibility contributes and capabilities of residential and commercial units.

First approach leads to yearly incomes of 51.5 € and 3614 € respectively for a residential and a commercial unit. These incomes are representative of the 40% of the total earnings coming from the balancing market participation, subdivided considering the different power contributes that residential and commercial units can supply. Remaining 60%, which amounts to 93623 €, has been considered as the yearly profit of the aggregator. It is not a purpose of this work to fully evaluate if the generated incomes justify the investments that would be involved to practically develop the aggregate structure. However, some easy-comparable considerations can be done regarding the residential case, realizing that incomes are almost the 6% of the yearly average electricity bill for a domestic unit. Moreover, the obtained results are strictly confined by the assumed problem hypotheses that could be implemented in further developments of this work. First of all, focusing on the considered flexibility, it results limited with respect to the one that could have been considered. To sustain this, it is sufficient to notice that, during winter season, the available flexibility is dramatically reduced since no heat system has been introduced. In fact, this would have led to an increase of the available flexibility since, as it occurs during the summer period, units thermal inertia could be exploited. Additionally, more and more importance is covered by the so called CHP systems, thanks to which it could be possible to combine heat and power production and, therefore, generate flexibility that could be exploited in the electricity market. With reference to the amount of considered units, it is important to recall that, due to computational limits, 30 user-type have been considered and then re-scaled. However, the achievable synergies are those related to 30 users that, instead, could have been incremented considering a larger sample. Finally, the vehicle to grid technology is becoming a very interesting matter for many companies in the energy sector. Moving from technical to economical considerations, this thesis focuses on providing balancing market services, disregarding others that could be considered in further developments of these work. Additionally, recalling the UVAM forward ancillary services market, it is possible to observe, from the simulated dispatching orders, that the minimum requirements settled in order to gain the fix remuneration of 30000 €/MW/*year* have been respected both during summer and winter seasons. Clearly, to be awarded of this sum, the variation has to be guaranteed for a certain amount of days, as reported in the previous chapters. In any case, looking at the participation coefficients, it is reasonable to consider that the units will be able to do that; moreover, the achieved power variations are higher than the minimum one required by TERNA, equal to 1 MW. Finally, MSD market trend is constantly increasing. All the cited technical and economic aspects could clearly affect in a positive way the considered economic analysis. In conclusion, with reference to the second approach, the economic evaluation has not been fully carried out, while the results have highlighted which are the actual capabilities of the residential users, without considering the commercial one. Although just an example was reported, the proposed evaluation could have been derived focusing on different time periods, power variations and elapse times.

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Appendix A

Kernel density estimation

There are many methods that can be used in order to obtain a probability density estimation, the easiest one is the histogram that can be used for *local density estimates*. Histogram is constituted by many adjacent rectangles, each of them represents a class of values and the amplitude of each class is represented by the rectangle base. The height of the rectangle represents the density frequency and it corresponds to the ratio between the absolute class frequency and the class amplitude; this means that the area of each rectangle represents the absolute frequency associated to the considered class. Many times is useful to represents the relative frequency of each class, this is obtained dividing the absolute frequency of a class by the sum of the absolute frequencies of every class; this leads to a normalization of the histogram. The sum of the relative frequency of each class equals 1, in this way a density histogram is obtained. Histograms present some disadvantages that can be summarized as:

- Not smooth resulting estimate;
- An observation belonging to a given class may be closer to the values of observations belonging to the neighboring class than it is to the values of its own class.

These problems can be solved by introducing a weighted local density estimate for each observation, aggregating them to achieve an overall density. A method of doing this is to exploit the *Kernel Density Estimation (KDE)*. An estimator of the following type can be adopted :

$$f(x_0) = \frac{1}{n \cdot h} \sum_{i}^{n} K \cdot (\frac{x_i - x_o}{h}) \tag{A.1}$$

where x_0 is the point at which the estimate has to be computed, x_i is the i-observation, K is the *Kernel function* and h is the bandwidth that controls the size of the neighborhood around x_0 .

Regarding the Kernel function it can have different shapes, the important properties that have to be respected in order to achieve significant estimates are that K has to be a non-negative, real valued, integrable function. For a wide variety of applications it is desirable that K matches the symmetry property and the normalization criteria (unitary area). The most common types of Kernel function are reported in Figure A.1.

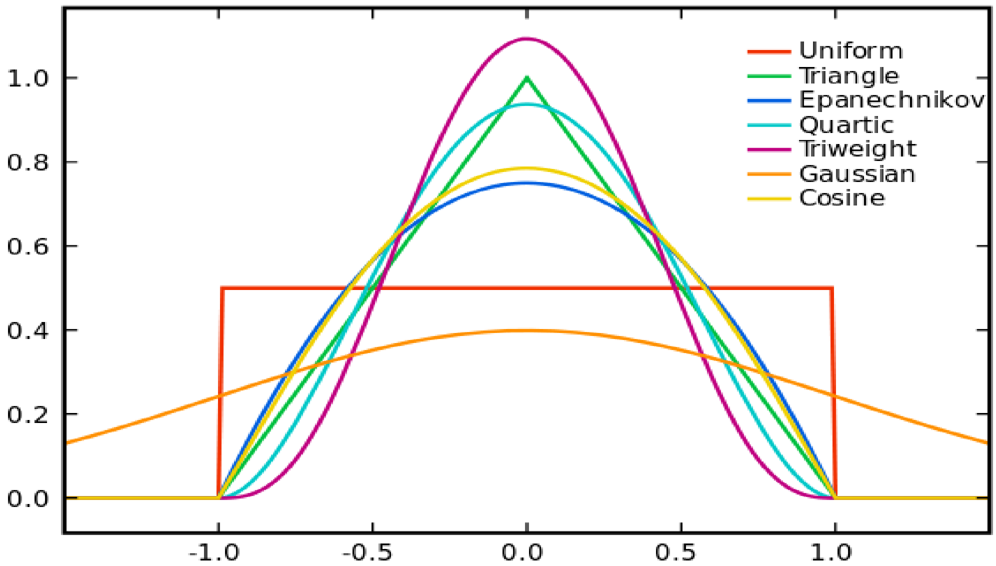

Figure A.1: Common type of Kernel function

These functions represent the window used to weight the density estimation in each point. In order to understand how these windows work, without entering in a deep mathematical analysis, some graphical representations taken by the website [22] are reported.

In Figure A.2, Figure A.3, Figure A.4 are reported different Kernel functions. The dots represents the observations, while their color represent how they are weighted by the windows, the lighter they are, the higher is their weight. The red line is the Kernel function, the dotted blue line identifies the value in which the estimate is carried out x_0 and finally the blue line accounts for the whole density estimation, summing all the red lines that would be obtained shifting the window over the whole set of samples.

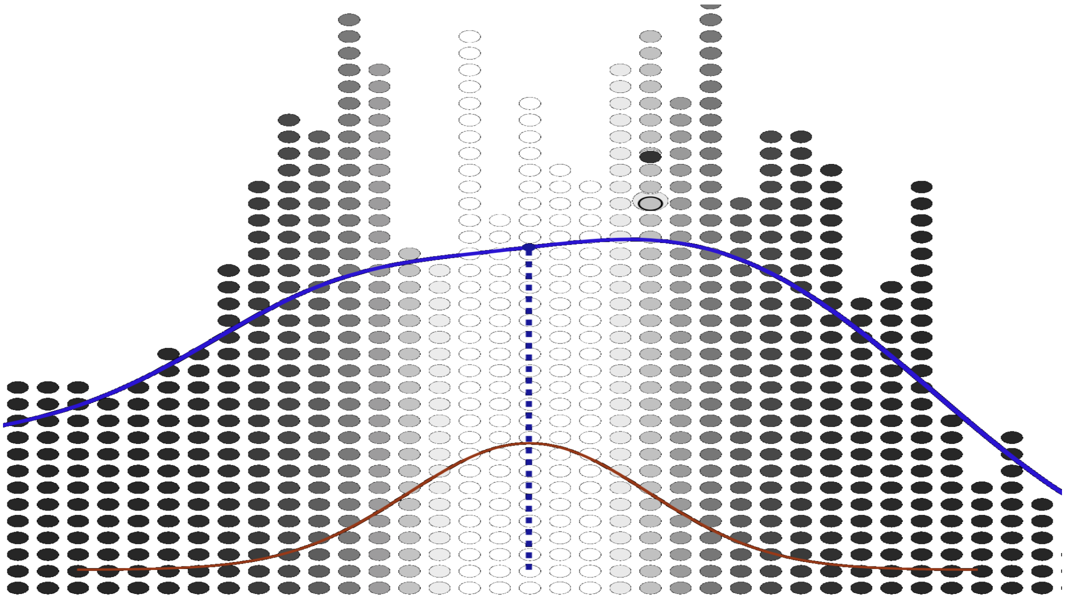

Figure A.2: Normal Kernel, Bandwith=1

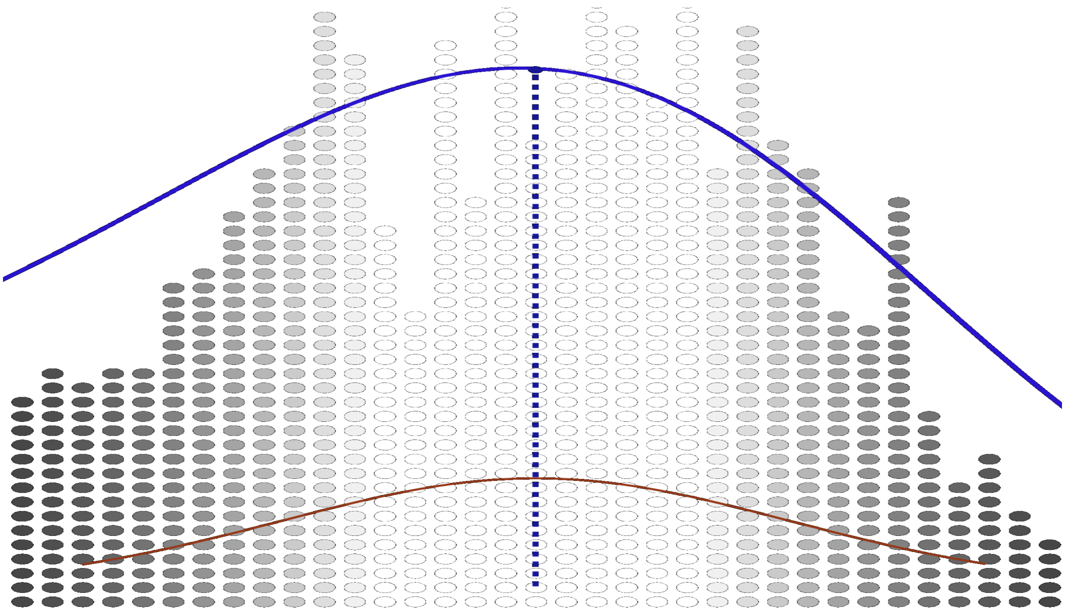

Figure A.3: Normal Kernel, Bandwith=1

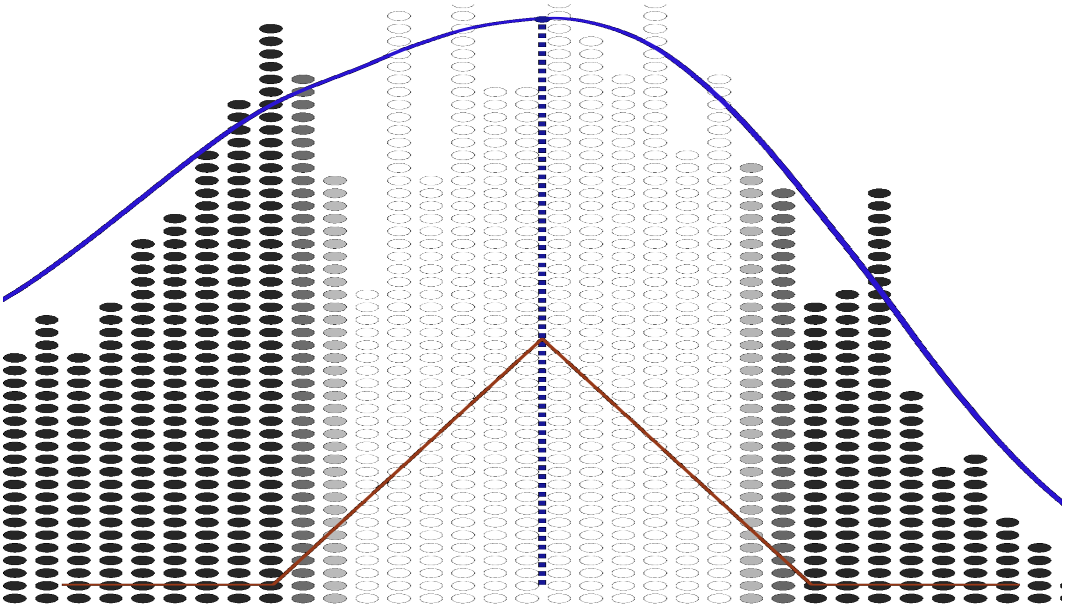

Figure A.4: Triangular Kernel, Bandwith=1

As observable comparing A.2 and Figure A.3, the bandwidth value influences the estimation result, in order to choose a correct bandwidth two main methods can be exploited; for the sake of completeness they are reported in the following:

- Cross-validation approach

$$argmin_h\left(\int f^2(x)dx - 2\sum_{i=1}^{n} f^2_{(-i)}(x_i)\right) \tag{A.2}$$

- Use the formula

$$h* = \left(\frac{\int K(x)dx}{n\sigma_K^2 \int f''(x)^2 dx}\right)^{1/5} \tag{A.3}$$

Concerning market data evaluation reported in this thesis, the bandwidth choice has been accomplished in an easier way. Particularly, since the trend of market offers is well known, the risk of choosing a too small bandwidth that highlights too many data peaks or to choose a too wide bandwidth that obscures relevant data information is low. With this regard, different simulations have been carried out and the observed results does not differ in a relevant way depending on bandwidth choice. Finally, the optimal bandwidth for normal kernel function has been chosen, this is internally computed by MATLAB and allows to obtain a good smooth probability density function that matches with the expected market trend for what concerns offer prices and acceptance probability relation.