POLITECNICO DI MILANO
School of Industrial and Information Engineering

MSc in Electrical Engineering

Vehicle to Grid in the scenario of virtually aggregated units: a case study

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Academic year 2018/2019

Alla mia famiglia

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Abstract

This thesis work assesses the potential of the Vehicle-to-Grid (V2G) and Grid-to-Vehicle (V1G) technologies, two smart charging options for electric vehicles that allow also the provision of ancillary services. The case study considers a company car park where all employees are provided with an electric vehicle. This car park is also part of a virtual unit in which the figure of an aggregator brings together several units of small size (units of generation, consumption and storage) to ensure the participation in the Italian Ancillary Service Market. In order to comply with the technical specifications of the car fleet and of the virtual unit, as defined in the Italian pilot project deliberations, the analysis has been developed through a numerical model of mixed-integer linear problem that maximizes profit, obtained as the difference between the proceeds obtained from the sale of energy on the grid and the cost due to the quantity purchased, net of the price for vehicles' recharging. The optimization model simulates the operation of the aggregate every 15 minutes, taking into account the energy balances, the limits on the available power according to the installed charging stations and the EVs presence, the economic data of the electricity market, the specific regulations on participation of two pilot projects (one for virtual units with different technologies and one for virtual units composed of only EVs), and finally the constraints of the state of the batteries according to the employees' needs. Once the general structure of the model was defined and implemented, 4 subproblems were distinguished, obtained considering the participation in two different pilot projects using V2G or V1G technology in each one. Several sensitivity analyses on the economic and technical parameters have made it possible to evaluate various aspects of these applications, both through daily simulations, to observe the trend of the offers, and annually, to evaluate their feasibility and profitability. After the optimisation problem, a further analysis of the possible economic scenarios was carried out, depending on the different incentives, already applied and not. The results show that these recent technologies, in addition to allowing a greater versatility of operation of virtual units and to provide ancillary services to the electricity grid, in some cases are economically advantageous.

Compendio

Questo lavoro di tesi ha valutato il potenziale delle tecnologie Vehicle-to-Grid (V2G) e Grid-to-Vehicle (V1G), due opzioni di ricarica intelligente per veicoli elettrici che consentono anche la fornitura di servizi di dispacciamento. Il caso studio è quello di un parcheggio di un'azienda in cui tutti i dipendenti sono provvisti di auto elettrica. Questo parcheggio, inoltre, si assume facente parte di un'unità virtuale in cui la figura di un aggregatore riunisce più unità di piccola taglia (unità di generazione, consumo e accumulo) per fare in modo di poter partecipare al mercato dei servizi di dispacciamento italiano. Per rispettare le specifiche tecniche del parco auto e delle due diverse unità virtuali considerate, così come definite nelle delibere dei progetti pilota Italiani, si è svolta un'analisi basata su un modello numerico di ottimizzazione lineare mista-intera, che massimizza il profitto, ottenuto come differenza tra i proventi ottenuti dalla vendita di energia in rete e il costo dovuto alla quantità in acquisto, al netto del prezzo dell'energia per caricare i veicoli. Il modello di ottimizzazione simula il funzionamento dell'aggregato ogni 15 minuti considerando i bilanci energetici, i limiti sulla potenza disponibile in funzione delle colonnine installate e dei veicoli presenti, i dati economici del mercato elettrico, le normative specifiche sulla partecipazione a ognuno dei due progetti pilota e infine i vincoli sullo stato delle batterie secondo le esigenze dei dipendenti. Una volta definita ed implementata la struttura generale del modello, si sono distinti 4 sottocasi, ottenuti considerando la partecipazione a due progetti pilota e l'utilizzo della tecnologia V2G o V1G in ognuno di essi. Diverse analisi di sensitività sui parametri economici e tecnici hanno permesso di valutare vari aspetti di queste applicazioni, sia tramite simulazioni giornaliere, per osservare l'andamento delle offerte, che annualmente, per valutarne la fattibilità e la redditività. A valle del problema di ottimizzazione si è svolta un'ulteriore analisi dei possibili scenari economici in base alle diverse incentivazioni, già in vigore e non. I risultati mostrano che queste recenti tecnologie, oltre a consentire una maggiore versatilità di esercizio delle unità virtuali e a fornire servizi ancillari alla rete elettrica, in alcuni casi si rivelano economicamente vantaggiose.

List of acronyms

ARERA	Autorità di Regolazione per Energia Reti e Ambiente
ASM	Ancillary Services Market
BEV	Battery Electric Vehicle
BSP	Balancing Service Provider
CDN	Content Delivery Network
DSO	Distribution System Operator
EDF	Earliest Deadline First
EM	Energy Market
EV	Electric Vehicle
F1	Fascia 1
FCFS	First Come First Served
GME	Gestore Mercato Elettrico
KKT	Karush–Kuhn–Tucker
LLF	Least Laxity First
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
NLP	Non-Linear Programming
PNIEC	Piano Nazionale Integrato Energia e Clima
PV	Photovoltaic
RES	Renewable Energy Sources
RSE	Ricerca sul Sistema Energetico
SoC	State of Charge
TSO	Transmission System Operator
UPM	Peripheral Monitoring Unit
UVAM	Unità Virtuale Abilitata Mista
UVAR	Unità Virtuale Abilitate per la Ricarica dei veicoli elettrici
V1G	Vehicle to Grid unidirectional flow
V2G	Vehicle to Grid
V2H	Vehicle to Home
VRES	Variable Renewable Energy Sources

1. Introduction

The increasing need to reduce climate-changing emissions worldwide is generating deep changes in every industrial sector and above all in the electric system. This entails a different range of sources and power generation plants, with an ever-increasing number of Renewable Energy Sources (RES) plants and generally in small distributed generation plants and a sharp reduction of thermoelectric power plants in operation leading to less incidence of programmable resources. A step-by-step evolution from a production focused in a limited number of large power stations is leading to a new arrangement, in which distributed generation (medium and low voltage) plays a more and more relevant role. In the aforementioned energy transition, a critical aspect concerns the ancillary services, those operations not referring to pure generation or consumption but that consist in modifying the exchanges of active and reactive energy between plant and network in order to ensure electrical parameters - frequency and voltage – to be maintained within strict limits.

As a matter of fact, these kinds of services have always been carried out by medium-large sized programmable generation plants, i.e. thermoelectric and hydroelectric, able to be modulated in power and speed with certainty ensuring relevant powers by acting on a small number of systems. The previous model is becoming unsuitable since the lacking thermoelectric plants in service are being replaced by RES plants, less suitable for size and characteristics, and source themselves of a greater need for reserve power.

That being said, the case study tackled by this work intends to evaluate the expansion of the audience of subjects that can offer regulatory services as a solution for overcoming these critical issues, in an aggregate form, and through the use of a quite new technology. In particular, the case study considers the Italian regulatory framework.

In this introductory chapter, some basic notions will follow, preparatory to the framing and understanding of the work done in this thesis: the structures and operating methods of the Italian electricity market will be described synthetically.

1.1 Electricity market basics

The Italian spot electricity market is structured in three sub-markets [1]:

- Day-ahead energy market (EM), where eligible producers, wholesalers and final customers can sell and purchase electricity for the next day in a single session. The GME –electricity market operator- acts as a central counterpart.
- Ancillary Services Market (ASM), in which the Italian transmission system operator (Terna) obtains the dispatching services necessary for the management and control of the electric system. Unlike the other two markets, it is only open to a limited category of operators authorised to offer certain services, called "ancillaries", which are remunerated not at a market equilibrium price but at the offered price (pay-as-bid), if accepted by the unique counterpart, Terna.
- Intra-day market allows eligible producers, wholesalers and final customers to modify the input and output programmes determined on the ASM.

The day-ahead EM is a wholesale electricity exchange market where hourly electricity blocks are negotiated for the following day and where prices, quantities traded and feed-in and off-take programmes are defined. It is organised according to an implicit auction model and hosts the majority of electricity trading transactions. The single session opens at 08.00 on the ninth day before the day of delivery and closes at 09.15 on the same day. During the opening period of the EM session, operators may submit offers indicating the quantity and maximum/minimum price at which they are willing to purchase and/or sell, to reflect an effective willingness to inject or withdraw electricity. After the bidding session, the GME activates the market resolution process. For each hour of the following day, the market algorithm accepts the offers in order to maximise the value of the trades, in compliance with the maximum limits of transit between zones. With regard to the purchase operations (demand curve), the GME has implemented an algorithm that, regardless of where the withdrawals take place, provides for the application of a single price on a national basis, equal to the average of the zonal weighted selling prices for zonal consumption.

The ASM is the tool through which Terna, in its role as grid manager, procures the resources necessary for the management and control of the transmission system, in order to resolve intra-zone congestion, create and maintain energy reserves and balance energy flows in real time. Indeed, in order to reflect the dynamic nature of dispatching, the ASM consists of 8 daily sessions. On the ASM, the offers express the willingness to vary the energy inputs compared to what is defined in the preliminary updated programme resulting from previous markets, and differ in upward offers and downward ones. The contracted time step is fifteen minutes and not the hour, as is the case for EM and intra-day market. All accepted offers are remunerated at the same price that they present (pay-as-bid methodology). A brief list of some of the services traded in this market is provided below:

- Secondary reserve; it consists of making available to the grid operator a power band served by an automatic device capable of modulating the input of electricity from a generation group on the basis of a signal processed and sent to Terna. The objective is to bring the frequency level back to its preset value in a short period of time (from a few seconds to one and a half minutes).
- Tertiary reserve; it consists in making available a power margin that can be activated in real time by means of a dispatching order from Terna. The objective is to support the secondary reserve and to allow the replenishment of the reserve margins after the occurrence of any contingency (activation times that vary between 15 minutes and one hour).
- Ignition; these are offers that provide for the ignition of a certain production unit ready for operation.
- Switching off; these are offers that provide for the shutdown or reduction of production to the technical minimum of a specific production unit.

2. Vehicle-to-grid in UVAM context

The electricity supply chain is subjected to strict technical constraints and based on energy exchanges contracted in a competitive but complex regulated market. By their nature, non-programmable renewable power plants greatly complicate the management of the electric grid and the interactions between market stakeholders. In particular, the inherent randomness of their primary sources (irradiation, wind) leads to a discontinuity of electricity output both on a daily and seasonal basis and to unpredictable discrepancies between production forecast and actual feed-in. These oscillating phenomena accentuate the difficulties of coordination of the electricity service, characterized by the need for instant coupling between energy demand and supply.

The applicable Italian dispatching rules provide that only the large production facilities - also called "relevant units", larger than 10 MVA, such as thermoelectric power stations and large hydroelectric power plants, provide the necessary resources for system control.

It can be understood that a possible solution can be found decreasing the minimum power threshold for taking part in the ASM to well below 10 MW in order to include all the already existing small-medium sized power plants. An extra contribution can also be given by load modulation and including energy storage systems, even if they are not enough spread yet.

Clearly the huge number of resources to be involved represents an additional effort in monitoring and controlling each plant. Such a limit can be overtaken by a new position acting as an aggregator named BSP, Balancing Service Provider, which can put together a certain number of distributed resources and, at the same time, offer the related services to the transmission system operator. In addition, the possibility of including units for the excess energy storage, according to grid demand, is considered a key factor for balancing the electricity grid in a scenario of high penetration of non-programmable sources.

2.1 UVAM definition

The possibility of offering flexibility services through a "virtual system" consisting of the aggregation of several units, which may be, alternatively or simultaneously, both consumption and production units, is currently being investigated in Italy through the pilot projects promoted by Terna. The results of these projects will provide useful information for the definition of new rules for dispatching.

The ARERA 300/2017 resolution [1], followed by further update deliberations by the same Italian authority (for energy, networks and ambience regulation), opened an experimental phase allowing new resources to take part in the ASM:

- not relevant generation units (smaller than 10 MW and/or not programmable);
- loads - characterized by a great rapidity of regulation, they can also offer adjustment bands both upward and downward, reducing or increasing the withdrawal from the network;
- storage systems – they can potentially offer all the aforementioned services and guarantee really short adjustment times, but the duration of the supply is bounded to the system capacity.

One of the Terna pilot projects fits into this context, defining UVAM (Unità Virtuali Abilitate Miste) as “mixed” units – i.e. the ones previously listed - virtually unified by an aggregator. They have been enabled to dispatch services such as congestion resolution, rotating tertiary reserve, tertiary replacement reserve and balancing. Compared to the previous resolution, some simplifications have been introduced, such as:

- in case of unidirectional services namely only downward (or upward) - reducing entries on the network or increasing withdrawals (the other way round)- the minimum (maximum) controlled power at least equal to 1 MW whereas the maximum (minimum) one at least equal to 2 kW;
- in case of bidirectionality, the controlled power range– maximum and minimum enabled power–set equal to 1 MW;
- Modulation in increasing (or decreasing) entries or modulation in decreasing (increasing) withdrawals in 15 minutes from the receipt of Terna dispatching order as for congestion resolution, rotating tertiary reserve, balancing and within 120 minutes as for tertiary replacement reserve;

- Services duration threshold of at least 2 hours as for congestion resolution, rotating tertiary reserve, balancing and at least 8 hours for tertiary replacement reserve.

The possibility of receiving a fixed remuneration, equal to 30 k€/year/MW, has also been introduced in the event that it is guaranteed to make offers during weekdays in the 2-8 pm time slot.

In the analysed scenarios, this additional advantage has not been considered; in any case, it is assumed that this remuneration will disappear over time, i.e. with the increase in the competitiveness of the UVAM compared to other traditional plants.

2.1.1 Structure and management

The stakeholders involved in managing a UVAM can be listed as follows:

- Aggregator (Balance Service Provider);
- Virtual aggregate units;
- Transmission System Operator (TSO) i.e. Terna;
- Distribution System Operator (DSO);
- Dispatching users.

The BSP, as UVAM owner, deals with the creation and technical and economic management of the virtual unit that have to be carried out in compliance with the requirements and obligations established at regulatory level. Moreover, in order to receive dispatching orders sent by the TSO, it has the obligation to define for each UVAM a physical control point, continuously monitored through the necessary tools and equipment. According to the network code, the physical control point has be connected with Terna systems so that the aggregate can be seen inside the control systems by the TSO - as it already happens with relevant generation units. Usually the connection is realized through CDN (Content Delivery Network) technology with at least two access points to the Terna communication network. The aggregator is also required, from the TSO, to send the baseline, namely the power program of the UVAM net of interruptible load consumption, for each quarter of an hour per day, in addition to the constant updating of technical data and possible dispatching unavailability of the managed UVAMs through SCWeb system.

From units owners view point, they can enter into a contract with the aggregator setting the availability of a capacity range modulation in order to share the earnings obtained from the market (according to a profit sharing logic).

As for DSO, its role is associated to the approval of aggregate points; in case of specific distribution network constraints, it can request the non-qualification, or a partial one (e.g. in terms of capacity range foreseen by the BSP), of a single unit even during the units service.

The one not involved in UVAM managing or services, but only in its creation, is the dispatching user: the qualification request need the approval of the users as units owners.

A central role is played by Terna; according to regulation definitions and network code adaptation, it allows the actual UVAM qualification subject to passing the technical tests and receiving the data needed for a right system operation. It is also responsible for dispatching orders (BDE) through its own IT systems and for defining aggregation perimeter of production or consumption units and storage systems (almost coincident with Italian regions). Among the requirements for the creation of a UVAM it is required that all the aforementioned units associated with it are equipped with the so called UPM - Peripheral Monitoring Unit- functioning as data collector for each point. Every monitoring system must send the data to the BSP concentrator, at the frequency set by the regulation (which depends on the power associated to the specific point). The UPMs must also receive modulation orders from the concentrator in the event that the UVAM receives a dispatching order from Terna.

2.1.2 Communication and BDE compliance

In order to measure the total energy exchange (entries and withdrawals) between UVAM and the grid, the BSP must be able to manage the communication between the concentrator and the UPMs involved. These latter send to the BSP concentrator all the data related to the single unit participating in the UVAM and can receive from it a modulation input. After that, the BSP is required to send for each of the UVAM managed, with a timing of 4 seconds, the total entries/withdrawals in terms of power equal to the sum of UPMs measurements (or, at least, measurement estimates) at each point of entry/withdrawal.

In case of receiving a BDE by Terna, the concentrator sends modulation orders to the individual points that constitute the UVAM. The choices on the modulation distribution between the units making up the UVAM is left to the aggregator that must do it ensuring that the system as a whole is able to implement dispatching orders in compliance with regulation times and methods. This modulation distribution among units can be done using more or less complex methodologies, such as optimization algorithms, taking into account both technical and economic variables (Dispatching Management System). Even the choice about methodologies and communication technologies between UPMs and BSP concentrator is up to the aggregator (which, in any case, must have approval by the TSO). This connection can be equally private or public as long as reliability, security, efficiency and data integrity are guaranteed.

An alternative, valid if the UVAM consists of a single unit, is the direct connection between the UPM and Terna, thus excluding the use of an intermediate concentrator, as long as the UPM is compliant with all the prescriptions for the concentrator.

As regards market offers, each aggregate can present up to 3 or 4 price quantity pairs in ex ante dispatching market on sale or purchase, depending on the UVAM enabling procedures. The observance verification of dispatching orders is carried out assuming as reference the aggregate baseline, notified from the BSP on the day ahead (D-1). According to the acceptance of quantities offered by Terna, UVAM owner is obliged to vary the entry/withdrawal of associated points with respect to its own baseline. The BSP is subject to the ordinary remuneration of the quantities accepted on the ASM. In the event of failed compliance with the dispatching order, the BSP is required to pay Terna a fee computed as the product between the market marginal macro-price and the quantity of energy not provided.

2.2 Vehicle to grid technology

The second pilot project considered includes storage systems that are functional for electric mobility, these being totally comparable (at the connection points to the grid where charging / discharging takes place) to other storage systems: the project is set up, therefore, also as an enabler of the "vehicle to grid" technology to the ASM.

The vehicle-to-grid (V2G) technology consists of the interaction between electric vehicles (EVs) and the power system allowing the aforementioned vehicles, through charging stations, to supply the grid providing tertiary reserve and balancing services as well as congestion resolution and, eventually, additional services including primary frequency regulation and voltage regulation.

To this end, the energetic benefits that proper management of charging can have on the load profile are very promising; as a matter of fact V2G is able to flatten the demand curve to an average value by responding as generators in peak demands. Moreover, balancing and ancillary services (primary, secondary, tertiary) could be provided to the grid in real time when these are required. These services are distinguished by the different time scales in which they operate – for the primary one is within 30 seconds from the moment it becomes necessary, for the secondary and tertiary is gradually a longer time period - and the ways in which they are activated - the primary change the power input based on the frequency measured locally whereas the other services are controlled by signals sent by the national network operator.

Even if the current regulation of Terna does not allow this type of aggregates to offer all services, technically it would already be feasible.

Another usage of EVs battery capacity, which differs from V2G technology for the command’s origin, is called Vehicle-to-Home (V2H): instead of having a network operator who wants to supply ancillary services to the grid, the V2H recipient is identified in the domestic energy “manager” who wants to increase self-consumption taking advantage of self-production or reducing peak power consumption, saving on costs related to the used power.

2.2.1 Short history and development

The technology behind the V2G was developed in Japan between 2009-2012 and is a native function of all cars adopting the Chademo DC charging standard. Nowadays it is not possible for cars adopting the CCS1 COMBO direct-current charging standard, even though international standardization groups are working towards this. In 2015 this technology was brought to Europe by the Enel Nissan partnership with the first applications in Denmark in August 2016 and at a later time in the United Kingdom; the first V2G-type charging stations arrived in Italy, thanks to an electric car sharing pilot project involving again the aforementioned partnership in collaboration with Ricerca sul sistema Energetico (RSE), although initially these systems were operated as normal unidirectional stations.

Looking at the 2030 energy scenario, the need for flexibility due to the increasing amount of power from VRES (variable renewable energy sources) will be likely equal to 70 GW [2] – 34% of Italian power consumption – or, in energy terms, 115 TWh (40 TWh plus 75 TWh from wind and PV systems respectively): from the mentioned report it came out that the needed storage estimate will account for 55 GWh. The National Energy and Climate Plan (PNIEC in Italy) foresees 1,6 millions of BEV for 2030 and, assuming 40 kWh for each vehicle battery [3], they would result in, theoretically, 64 GWh of available energy for ancillary services, even more than the necessary storage capacity for VRES.

2.2.2 Basic functioning

A V2G charging system consists of a bidirectional power inverter namely AC/DC converter plus DC/DC converter. Depending on the commands it receives from the network operator, the AC/DC one can rectify the AC power from the power grid to the DC power during the EV charging mode (like a common recharging station) or alternatively, in the discharging mode , invert the DC power to the AC power before injecting back to power grid (like any other generator) with a maximum bandwidth of typically 10 kW order. The bidirectional power flow is controlled by the DC-DC converter, acting as a buck or bust converter, by means of current control.

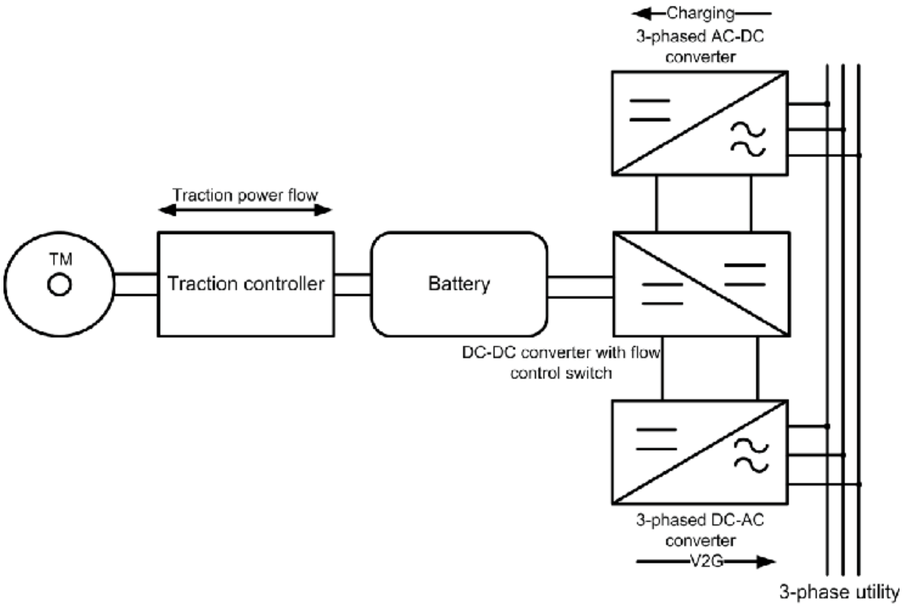

Figure 1 Block diagram of the charger and V2G integrator [4].

Other than providing active power support, bidirectional V2G has the capability to supply reactive power for grid voltage regulation. This service can be implemented with adequate sizing of charger capacitor (i.e. the DC link between AC/DC and DC/DC converter) and proper control switching. Power factor regulation is also one of the premium services offered by the bidirectional V2G technology, which can reduce power losses in the power grid.

2.2.3 Charging strategies

It is clear that an EV connected to a V2G system alone is not sufficient to support the electrical system: a set of EVs batteries is necessary to provide a significant contribution in the electricity market, and above all, many of the markets that V2G can make the most economic value participating in - such as frequency regulation - requires a minimum power capacity in order to participate (1 MW as for UVAM project). For this purpose, the aggregator proposes to aggregate vehicles that do not belong to it, but also other resources, such as the modulation of user loads, that of small cogeneration plants, etc. to sell services on the ADM. Beyond the technical and market required grouping capacity of an aggregator, an aggregator with a fleet of V2G-capable EVs can also offer stability and flexibility as a market participant through the implementation of predictive and/or control algorithms. Aggregators are the key connection between the grid and the vehicle, as they receive the power dispatch signal from the electricity operator, and then send the relevant information to the V2G-capable EVs in the fleet.

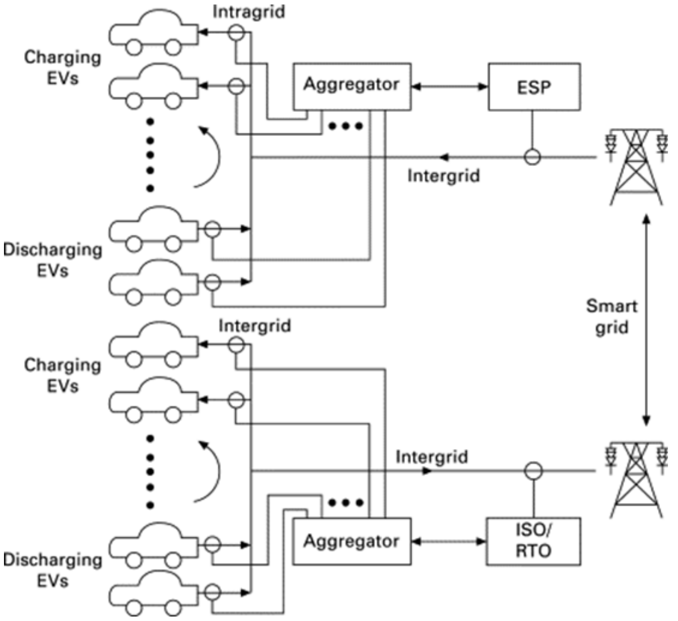

Figure 2 Aggregated dual-grid V2G framework [5].

As regards the charging mode, when future data are unknown, the charging scheduling algorithm makes decisions based on only the causal information available to the scheduler, i.e. without having the entire input available from the start but processing it piece-by-piece. Because of the absence of data statistics, algorithm performance is generally evaluated in the worst-case scenario through competitive ratio [7], defined as the maximum ratio between the cost achieved by an online algorithm and that achieved by the optimal offline algorithm over all possible input sequences (e.g. the EVs arrival patterns, charging demands,...). The main online control strategies include:

- FCFS, First Come First Served, charging in order of their arrival time;
- EDF, Earliest Deadline First, charging in order of their deadline;
- LLF, Least Laxity First, charging in order of lowest laxity where

$$Laxity = 1 - \frac{time\ required\ to\ charge}{total\ time\ at\ the\ lot}$$

These classic algorithms often need modifications to fit in the structure of EV charging problems e.g. sometimes they are combined with pricing (incentive of cheaper electricity rates during periods where the network is less loaded) and other control schemes.

2.3 UVAR definition

Conditions and terms of participation for EVs to the dispatching market are already declared in the definition of UVAM although these units are not originally thought and structured for EVs' needs. For this reason a particular regulation for the aggregates involving only charging stations (UVAR) is being discussed.

The main aim is promoting the usage of EVs batteries as providers of electrical system services by exempting payment for energy withdrawn from charging stations - as already happens for stationary storage and pumping systems. As for regulation for participation to the electricity markets, those vehicles included in a UVAR are regulated by the following hypothesis:

- Minimum threshold for adjustable power of 0,2 MW;
- Minimum duration and time slots defined according to mobility needs;
- Charging stations equipped with meters for hourly measurements;
- Extended experimentation and number of services provided by charging stations – including short duration and quick response ones.

On the other hand, in order to guarantee fair charges application for energy withdrawals, exemptions are foreseen for network tariffs and variable components in the following cases:

- withdrawn energy because of services to the dispatching market;
- withdrawn energy first intended for other reasons but later reinjected into the grid for market needs.

3 Case study

This chapter will introduce the mathematical model developed in order to perform a techno-economic analysis of a EVs parking facility enabled to act as a distributed energy storage system providing services to the power grid. The objective will be to quantify the economic conditions that would make this technology feasible and convenient for the users, looking at both their perspectives, namely as consumer and provider at the same time.

For this purpose, an optimization model has been implemented, described in detail below, which takes into account both technical constraints and economic aspects. In the first paragraph, emphasis will be placed on the range of EV parking facilities, especially highlighting peculiarities and advantages of the chosen use case; later on, input data and initial assumptions have been introduced, specifying sources and/or justifying every degree of freedom in order to keep the problem as real as possible. Then, preliminary computations regarding the car fleet have been carried out to have a reference baseline for the optimization process. In order to set the implementation work at a theoretical and mathematical level, essential notions and definition about optimization problems have been recalled, in addition to an exploration of algorithms and software from computational point of view. Coming back to the case study, the development of a dispatching strategy has been carried out through the expression of the objective function, designed for the general case of vehicle to grid in the context of mixed virtual units (UVAM), without considering any incentives specifically intended to encourage the use of this technology.

In the last part of this paragraph, the individual parts that make up the optimization model will be discussed in detail, appropriately quantifying each parameter in the equations. Finally, a specular analysis was conducted for an additional model, not developed, to obtain disaggregated results, i.e. establishing the share of each user in technical and economic terms.

3.1. Use Case: workplace charging

The following case study considers a limited number of EVs clustered in a parking facility located in RSE, a research institute based in Milan, in which vehicles can offer services to the grid during their charging process.

As regards the use case, in other words the kind of user and corresponding location, the choice fell on a growing one; an Italian statistics about the most used charging spots, in terms of percentage, reveals that:

- 87% represents “individual” private charging (wall-box, home charger);
- 8% “collective” private charging (workplace, condominium space, …);
- 4% charging in locations open to the public (road, park, …);
- 1% on the road.

In spite of most EV early adopters have access to home charging, workplaces spots, as well as other locations aggregating private users, are gaining more and more attention basically thanks to a faster charging rate, a quite defined usage time window i.e. mainly daytime and finally the possibility of forming “charging demand groups” in order to obtain more affordable charging prices from mobility service providers –it is not possible that prices applied to locations accessible to the public are equal to the domestic ones. In some countries, e.g. in the Netherlands, charging spots in locations open to the public have differentiated prices depending on the contextual usage of renewables namely on charging station self-consumption.

Moreover, as falling battery costs, public policy and consumer needs will led workplace charging on the rise. Particularly for those living in apartments in urban centres, it can be difficult to have an accessible spot where their vehicle can charge overnight whereas for more rural drivers, residential charging alone may not be enough to overcome range anxiety. Looking at the European and North American scenarios, a research carried out by Wood MacKenzie [7] shows that (Figure 3) workplace charging markets could surpass a combined 500,000 charger units in 2022, and reach over 1.25 million chargers by 2025. Europe has the potential to contribute 700,000 of those units, thanks to the higher proportion of people living in apartment blocks.

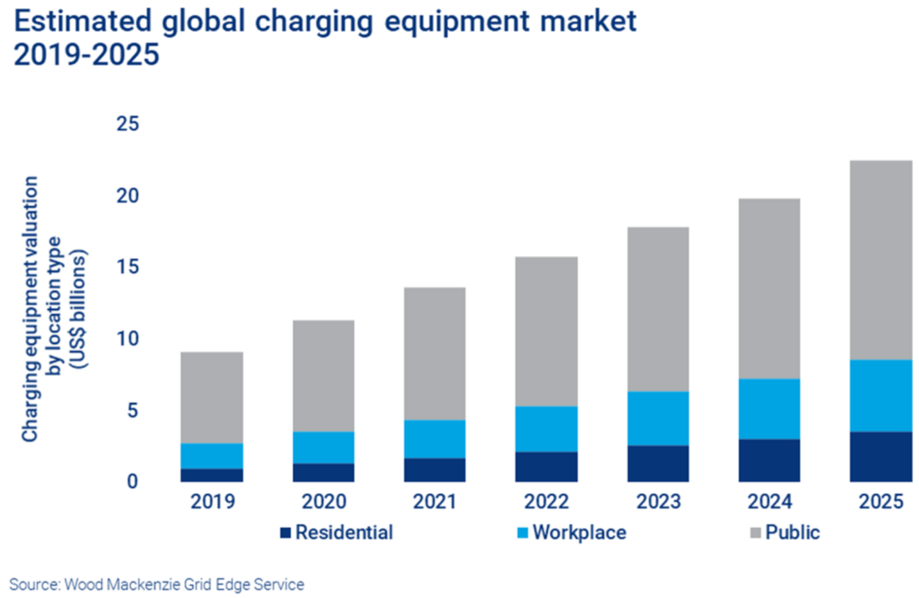

Figure 4 Charging stations spread in European and North American markets.

3.2 Input data

The available data for the problem, used into the optimization model as constants, address the solver to a unique optimal solution. Many and different optimization iterations can be carried out varying properly only some of these parameters, a priori, as well as through a sensitivity analysis a posteriori, observing their influence on the results.

Given to the strict link between starting data and the resulting outputs, all starting parameter will be afterwards justified either specifying the origin, in case of actual data, or showing the reasoning behind the postulated ones.

In the pre-processing analysis, the company spreadsheet including date, time of departure and arrival has been imported to deduce the total amount of time for charging every vehicle battery and offering services to the grid. (It has to be said that employees privacy has been respected since, for every clocking in/clocking out, there are no names or identification numbers, and even if they are in alphabetical order, the order cannot be the same between one day and the next one.)

As a first approach, an extrapolation from this dataset i.e. a single day from the whole period (from January 2 to December 31, working days mainly) was used to let the drawing up of simplified model equations, with a limited number of variables and constraints. For instance, Figure 5, referred to 8th January 2018, reports the total amount of vehicles during the whole day.

Indeed, in choosing the time interval, it was considered appropriate to follow the UVAM specifications about response time stated in the ARERA 300/2017 resolution: in case of services such as congestion resolution, rotating tertiary reserve and balancing ones, modulation in increasing entries or modulation in decreasing withdrawals (and the other way around) have to happen within 15 minutes from the receipt of TSO dispatching order. In this sense, identifying the quarter of an hour as the minimum step for the optimization problem, data, variables and constraints have been discretized on this basis.

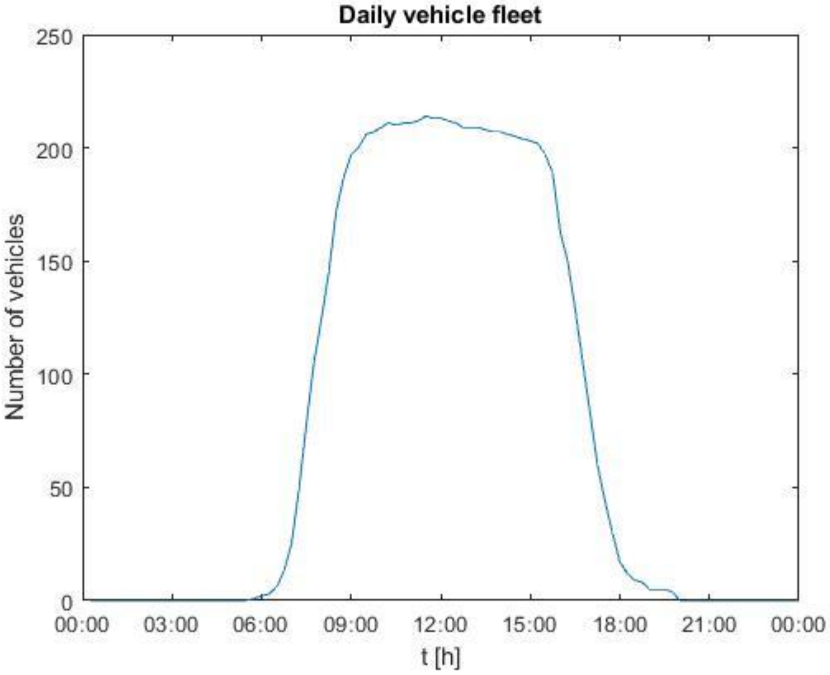

Figure 6 Data extrapolation of the company car fleet (reference date: 08/01/2018).

In the simulation developed, only the balancing service was considered. The relative price of offers, upward or downward depending on the case, is defined on the basis of the offers value of previous periods on the dispatching market. In particular, it has been elaborate and imported the average, hour by hour, of the historical prices of the offers, upward and downward separately, accepted during all the months of 2018. [8]

The upward offers are also called sale offers, whereas the downward ones are takeover bids, since the reduction in input corresponds theoretically to a repurchase of part of the energy previously contracted in the other previous market sessions. From this point of view, an offer to sell will typically be made at a price higher than the zonal price of the energy market (EM), as otherwise it would be strategically useless to keep bands of energy unsold from previous markets, if no extra earnings are expected. In addition, it is known that the network operator will always tend to need to obtain reserve margins or other services. In a specular way, purchase offers tend to be presented at a lower price than that of the day-ahead EM, with the intention of buying back at a reduced cost a quantity of energy already previously remunerated at a higher price, by exercising a gain without actually activating the virtual unit. This behaviour should not be understood strictly in a speculative sense, since it should not be forgotten that these users provide services that are essential for the security of the electricity system and for the continuity of energy supply. Since, due to the nature of the EM, operators are subject to discontinuous and unsecured revenues, it is natural that actual energy transactions are remunerated at specific profitable prices. In general, for every quarter of an hour of trading Δt, the following inequality is always valid:

$$P_{min,buy}(\Delta t) < P_{av,buy}(\Delta t) < P_{EM}(\Delta t) < P_{av,sell}(\Delta t) < P_{max,sell}(\Delta t)$$

- P_{EM} price on the day-ahead energy market,
- $P_{min,buy}$ minimum price accepted in purchase,
- $P_{av,buy}$ average price accepted in purchase,
- $P_{av,sell}$ average price accepted in selling,
- $P_{max,sell}$ maximum price accepted in selling.

Obviously, a system that provides this type of service, in competition with others, will tend to offer a price of compromise between personal gain and a high probability of being worthy of acceptance.

The following graph shows the average prices accepted in the EM during 2018, revised on an hourly basis, with respect to the constant value of the average energy price during the F1 time slot (8 am - 7 pm).

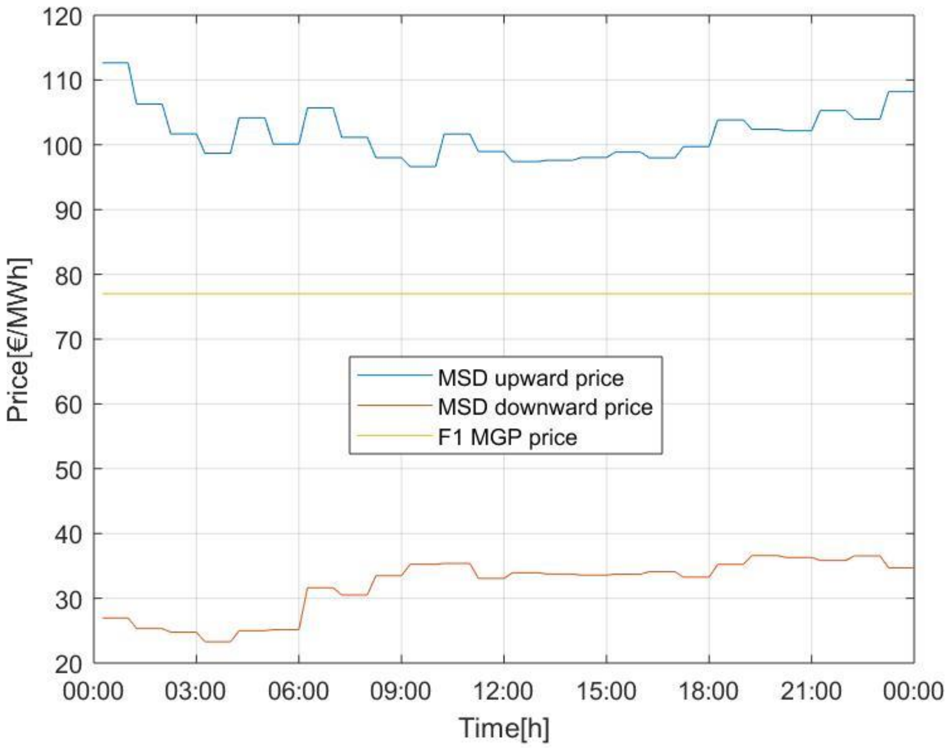

Figure 7 $P_{av,sell}$ and $P_{av,buy}$ average prices with respect to P_{EM} in F1 time zone.

3.3 Energy and Power Baselines

The first steps have been the drawing up of a simplified model on a limited period, a single day, with a limited number of variables and constraints. The stability and functionality of each addition has been gradually verified through the visualization and interpretation of the outputs.

Before proceeding with the optimization problem to analyse the possibility of participating in the EM, it is necessary to establish the basis from which to start, the initial conditions defined by the parking infrastructure (charging stations) and the technical parameters of the vehicles, and the timing of a workplace parking. The analysis that follows refers to the calculation of a daily baseline, in terms of power and energy, to charge the whole car fleet through the FCFS control algorithm with constant power. This baseline has been taken as a reference in order to realize every upward and/or downward power offer.

The initial and supposed assumptions about the parking are

- **Number of charging stations** (plausible estimate, considering a car fleet of about 300 EVs) : $n_{c.s.} = 100$;
- **Charging station power**: $P_{c.s.}$ = 15 kW;
- **Battery capacity for each vehicle**, same capacity of one of the most spread vehicle model: E_{max} = 40 kWh;
- **Discretization time**: Δt = 15 minutes;
- **Average initial and final state of charge** of each EV ($SoC_{starting}$, SoC_{final}) defined as

  $$SoC(t) = \frac{\int_0^{E_{max}} P(t) \cdot dt}{E_{max}}$$

  in order to reach a target of approximately 89 km of autonomy, enough to ensure a work-home roundtrip: $SoC_{starting}$ =0.5 , SoC_{final}= 0.9 .

By selecting the chosen analysis day, the program takes the spreadsheet with the arrival and departure of each vehicle and transforms it into a binary matrix where each column represents the vehicle presence (1, otherwise 0) on the selected day as a function of time. Each vehicle has to be charged with

$$E_{charging} = E_{max} \cdot (\Delta SoC)$$

Where

$$\Delta SoC = SoC_{final} - SoC_{starting}$$

Then, knowing from the binary matrix how many hours each vehicle has been parked, the single load profile can be obtained with the computed energy $E_{charging}$ divided by that time period; the total power load profile was achieved considering the binary matrix of cars presence times the single load profile. In the end, deriving n as vehicles number and using $P_{baseline}$ as previously described, the obtained energy baseline can be found as follows:

$$P_{baseline} = \sum_{i=1}^{n} P_{EV,i} = P_{EV,i} \cdot \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 0 \end{bmatrix}$$

$$E_{EV.i} = SoC_{starting,i} \cdot E_{max} + \int P_{EV,i}\, dt$$

$$E_{baseline} = \sum_{i=1}^{n} E_{EV.i} = n_{EV} \cdot SoC_{starting} \cdot E_{max} + \int P_{baseline}\, dt$$

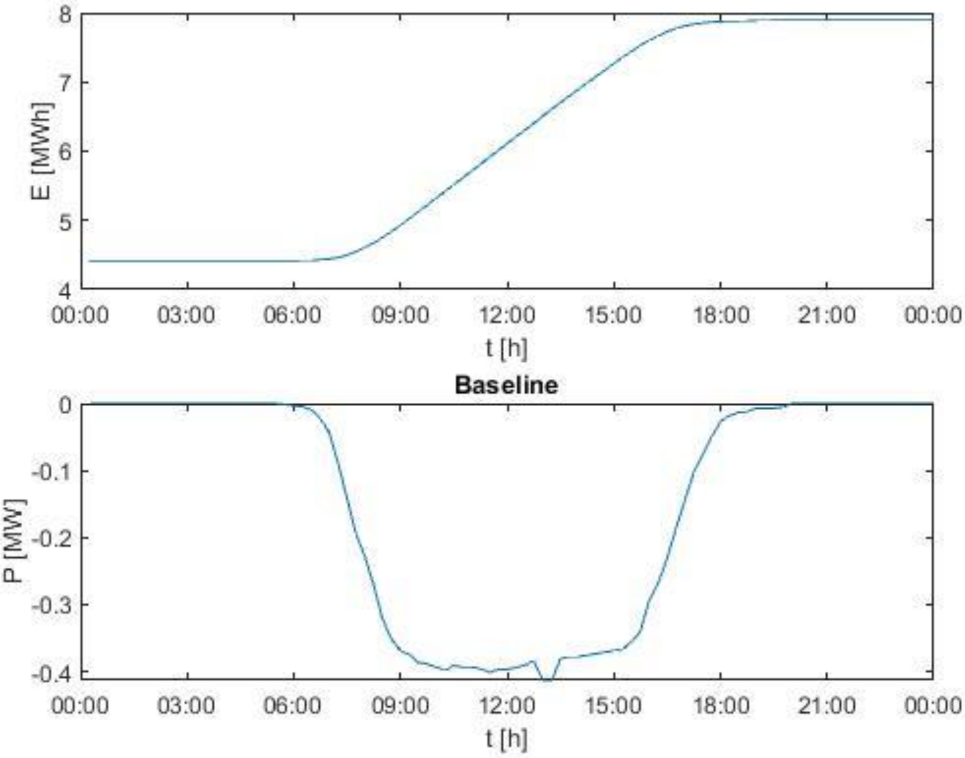

Figure 8 Daily Energy and Power Baselines (reference date: 08/01/2018).

3.4 Optimization model

Optimization problems are usually used in scientific and technological disciplines to obtain numerical values of system variables in order to minimize (or, equivalently, maximize) a specific parameter which is function of the variables themselves; therefore it consists in researching stationary points of the objective function, i.e. the function to be minimized.

3.4.1 LP and MILP definitions

In a first approximation, optimization problems are divided in two subcategories: linear and non-linear. Generally speaking, a canonical model of a non-linear programming problem (NLP) can be written as follow:

$$\min_{x} J(x)$$

$$h(x) \geq 0$$

$$g(x) = 0$$

where the theoretical components are represented by:

- Objective function $J(x)$;
- Decision variables;
- Constraints - equalities or inequalities which bound the aforementioned variables in a certain domain or link themselves to the others.

Moreover, it's useful to define the followings:

- Feasibility set - set of values allowed by constraints
$$\Omega = \{ x \epsilon \ \mathbb{R}^n : h(x) \geq 0, g(x) = 0 \}$$

- Global minimizer - the only point in the feasibility set in which the objective function has the minimum value
$$x^*: \ J(x^*) \leq J(x) \ \ \forall x \ \epsilon \ \Omega$$

- Local minimizer – the only point in its neighbourhood, and in the feasibility set, in which the objective function has the minimum value
$$x^*: \ \exists \mathrm{N} \ of \ x^*: \forall x \ \epsilon \ \mathrm{N} \cap \Omega \quad J(x^*) \geq J(x)$$

The model resolution aims to vary the variables numerical values, respecting the constraints they are subject to, in order to optimize the objective function. As soon as the stationary point of the objective function has been reached, it is possible to go back to the numerical values variables take in the optimal solution. These values have to be considered as the analysis results since their combination allows to optimize the function of interest.

As already said, optimization problems can be classified as linear or non-linear, as well as, as for decision variables and constraints, continuous, integer or mixed-integer linear programming. In this specific case, as it will be seen later in detail, the presence of both continuous and integer variables inscribes the problem inside the set of MILPs, Mixed-Integer-Linear-Programming, whose canonical form is:

$$\min_{x \in \mathbb{Z}^n,\ y \in \mathbb{R}^n} \quad c^T x + \ d^T y$$

$$A\,x + B\,y + f \ \geq 0$$

$$C\,x + D\,y + g = 0$$

At a theoretical level, the objective function solutions field can be intended as a N-dimensional space, with N as number of system variables. It is recalled that, in case of MILP, some variables are free to vary continuously whereas some others are necessarily integer numbers; that means the solutions field has both continuous and discrete dimensions. Inequalities, representing constraints, constitute plane sections of the N-dimensional space bounding variables variability and, in case of convex constraints, define a unique N-dimensional polytope. Due to the continuous variables presence, this hyperspace region is made of an infinite number of points that, interacting one another in the objective function, implies the latter can assume infinite different values. For simplicity sake, only a polygonal region i.e. a bi-dimensional case is depicted.

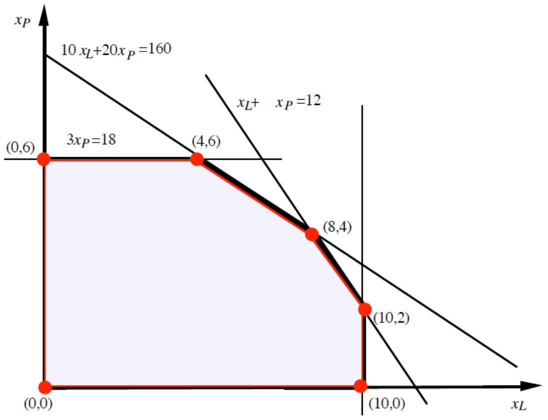

Figure 9 Optimization problem (LP) example: bi-dimensional solutions field.

In the previous LP bi-dimensional problem example, the objective function consists in a plane surface, linear function of the two decisional variables. Once the region of possible solutions has been reduced through constraints, represented by intersectional straight lines, it's mathematically guaranteed that function maximization is obtained in one point of the allowable region (i.e. the feasible set).

From a graphical view point, that can be depicted through a moving straight line towards the maximum direction of the function until the reaching of the optimal solution into the border of convex polygon.

3.4.2 Implementation algorithm and solution

Considering the infinite range of possible solutions despite the constraints existence, it's necessary to use a computational algorithm that let all the variables change their values following an increasing trend of the resulting objective function leading to its maximum. In order to solve such problems, above all if the decision variables are at least three-four, analytical approach is either insufficient or computationally expensive, numerical methods are required, using a set of software based on complex computational algorithms, specifically created for this purpose.

Extending the problem to N dimensions, the linearity of objective function as well as of the constraints, ensures that, if the problem is bounded in the direction of maximum growth, optimal solution will always be placed on a convex polytope vertex. Instead of exploring all the vertexes, the LP solution will be found using the so-called "Simplex algorithm" which is able to reach quickly the optimum moving in a smart way through the vertexes, even in case of thousands of variables.

Generally speaking, first-derivative tests used in linear and non-linear problems are the Karush–Kuhn–Tucker (KKT) conditions.

These are necessary conditions for the local optimisation of a point x^*. They involve a condition on the gradient of the Lagrangian function, defined as the sum of the objective function and the constraints, each weighted by a coefficient called Lagrange multiplier. The necessary conditions of the first order, i.e.

$$g(x^*) = 0$$

$$h(x^*) \geq 0$$

$$\nabla \mathrm{L}(\mathrm{x}^*, \lambda^*, \mu^*) = \nabla \mathrm{J}(x^*) - \nabla \mathrm{g}\,(x^*) \cdot \lambda^* - \nabla \mathrm{h}\,(x^*) \cdot \mu^* = 0$$

$$\lambda^* \geq 0$$

$$h_i(x^*) \cdot \mu_i^* = 0$$

are a set of equations and inequalities involving x^*, λ^*, μ^*; in the convex case these conditions are also sufficient. So, e.g., in case of non-linear problems with equalities constraints only, writing the Lagrangian function and the KKT conditions of the first order, the problem is ascribable to a system of linear equations in x^*, λ^*, μ^* very efficiently solvable. More generally, in the case of inequalities constraints, most of non-linear problem-solving methods consist of iterative methods trying to converge to points that meet the KKT.

As for integer or mixed-integer problems, usually the solution is harder to find with respect to the linear counterpart. First of all they are never convex and, in spite of the relevant reduction in number of possible solutions (a finite number), it is not possible to recognize definite boundaries since the hyperspace is a N-dimensional lattice made of discrete points.

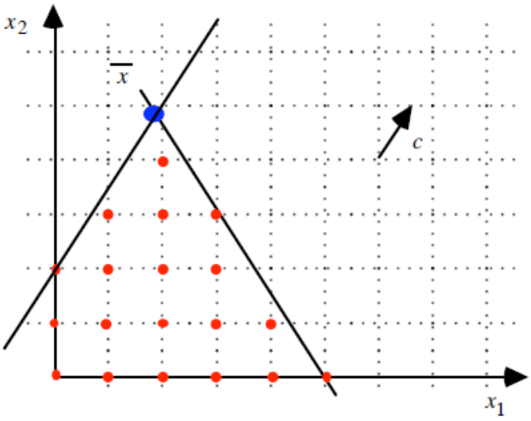

Figure 10 Feasible set and optimal solution of a MILP.

In these cases, the simplex algorithm is ineffective since the optimal solution is not in a vertex of the feasible set; other combinatory algorithms are used, mainly divided in two options:

- Cutting planes method;
- Implicit enumeration method – the feasible set is efficiently explored.

Among the main implicit enumeration methods, the well-known branch-and-bound algorithm break up the whole problem in subproblems easier to be solved, fixing some variables values at different levels and creating branches of possible solutions. Going on with the analysis in a enumerating order implied in every node, some branches are gradually discarded, demonstrating their "non-optimability" and adding narrowing constraints (bounds) to the variables values and therefore thining out the lattice of solutions to be found.

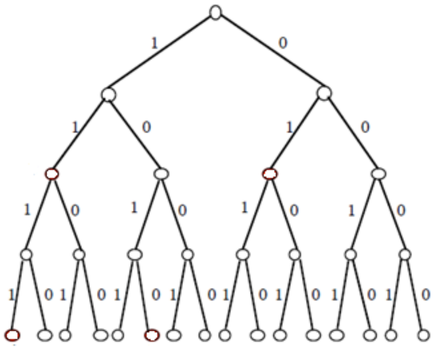

Figure 11 Branch and bound algorithm: 4 binary variables.

In the worst case, every solution has to be explored; indeed it's highly recommended a reduction in integer decision variables to make the problem treatable.

MILPs can also be solved through halfway computational methodologies f.i. through the "branch-and-cut" algorithm which approaches the problem finding, firstly, the so called "relaxed" solution i.e. that obtained not considering the variables integer nature and localizing the optimal border. Then, following the branch-and-bound similar reasoning, it analyses the discrete nodes of integer variable in the surroundings of the continuous border, gradually adding some cutting planes that intersect the most probable points, narrowing the feasible set. The final solution can be reached interchanging periodically relaxed analysis with more and more defined nodal ones.

3.4.3 Programming language and software interface

After having defined the model, MATLAB has been chosen as environment and programming language through which to implement it. The concept of software that provides a programming language to model an optimization problem, and software that implements the resolving algorithms, or solvers, must be discerned; MATLAB is part of the first set. Despite it provides an optimization toolbox, with functions and structures dedicated to optimization problems, this language was not specifically designed for handling these kind of problems: the definition of objective function, constraints and solution parameters is required in matrix form. The consequent difficulty in managing a large amount of data in such a way has led to the decision of using a software interface, YALMIP, which allows the user to write the problem in a symbolic form, and then translate and make it understandable to the solver. This open source interface automatically detects user problem and selects a suitable solver or, if it's not available, tries to convert the problem to be able to solve it.

The optimization problem addressed in this thesis involves a large number of constants, variables and constraints. It's enough to say that most of case study variables are on an quarter of an hour basis; for the whole analysis that aims to optimize the V2G service for a year, a single variable translates into 35040 variables. For an entire optimization, it is not surprising that every single iteration includes the combined calculation of thousands of equations. Consequently, due to computationally expensive resolution, a particular solver to be used is specified through the settings of YALMIP optimize function, i.e. CPLEX, a well-known and widely used large-scale solver, chosen because of its efficiency and robustness. It solves linear and quadratic optimization problems with continuous and integer variables, both convex and nonconvex quadratic objectives and constraints. For integer problems, therefore for this mixed integer case too, available algorithms are advanced branch-and-bound with presolve, feasibility heuristics, and cut generators. Other advantages are the possibility of concurrent optimization by several methods to determine best choice and special facilities for infeasibility diagnosis.

Table 1 General structure of the model implemented in MATLAB

Pre-processing	Yalmip path inclusion
	CPLEX setting up
	Excel files import
	Workspaces import
	Initialising matrices of results
Costants definition	Time intervals and horizon
	EVs specifications
	Charging stations specifications
	MSD and MGP prices
	Network, systems and other charges
Preliminary computations	Matrices of present EVs (function)
	Energy baseline (function)
	Power baseline (function)
	Battery deterioration
Model creation	Model expression - UVAM and UVAR scenarios
	Solver options
Variables definition	Selling power offer
	Buying power offer
	Upward binary variable
	Downward binary variable
Objective function definition	Objective function computation
Costraints definition	Energy technical constraints
	Power technical constraints
	Offer timing - UVAM and UVAR deliberation compliance
	Offer tresholds - UVAM and UVAR deliberation compliance
Other parameters of interest	Daily costs including energy prices and charges for every scenario
	Total costs including energy prices and charges for every scenario
	Costs comparison with respect to the basic case
	Power offers analysis
	Yearly exchanged energy
	Residual energy amounts
Post-processing	Display of solver diagnostics
	Display of total computational time
	Results conversion from interface type to approximate numeric type

3.5 Research objectives and boundaries

This case study simulation, i.e. a workplace parking enabled to the vehicle to grid technology, results in a optimization problem on an annual time horizon with a high number of constants and constraints, essential to obtained both variables to be defined and the final research objective.

For instance, for each single decision variable x_i, defined on 15 minutes time steps (Δt) within the whole time horizon (T)

$$x_i = [\ x_i(\Delta t_1), x_i(\Delta t_2), x_i(\Delta t_3), \dots x_i(T)\ ] = x_i(\Delta t) \qquad \Delta \mathrm{t} \in \mathbb{N} \text{ in } [1\ ;\ \mathrm{T}]$$

A constraint for each time interval can be defined:

$$a\ (\Delta t_i) \cdot x_2(\Delta t_i) + \ x_5(\Delta t_i)\ \leq\ b \cdot x_6(\Delta t_i)$$

corresponding to a technical limitation or special compliance with the UVAM or UVAR resolution. Considering for example the presence of 3 quarter-of-an hour variables (power, energy ...) to be optimized, each with 3 constraints (range, ...) we have a total of 3 x 3 x 25632 = 230688 values to be optimized. This gives an idea of the computational burden of the problem faced when the variables at stake are in greater number, as it will be shown below.

It should be remembered, however, that the aim is the development of a quarter-of-an-hour dispatching strategy conducted a priori with respect to the overall assessment of the possible advantages and, therefore, to the profitability in enabling services to the network compared to the standard case.

3.5.1. Objective function

The objective function, useful to underline the differential revenue between the case study and the baseline case, is the core of the model. In chapter 5 it will be explained the procedure with which the base case is preliminarily computed, that is the parking estimated cost with the V1G function only, starting from the real and historical available data. In addition, the different revenue will be compared in the case of workplace parking in the case of participation in the two different pilot projects briefly described in chapter 2.

As for the target function, if written in terms of profit, it can be expressed as

$$
\begin{aligned}
Objective = {} & \max_{x} J(x) \\
& = \left(\sum_{\Delta t=1}^{T} (\sum_{b=1}^{B} Benefit\,(j\left(P_{upward}(\Delta t);\ p_{upward}(\Delta t)\right)) \right. \\
& \left. - \sum_{c=1}^{C} Cost\left(k(P_{downward}(\Delta t);\ p_{downward}(\Delta t))\right) \right) \cdot \Delta t
\end{aligned}
$$

With

- B total number of offer benefits;
- C total number of offer costs;
- $P_{upward}(\Delta t)$ amount of injected power [MW];
- $p_{upward}(\Delta t)$ prices of injected energy [€/MWh];
- $P_{downward}(\Delta t)$ amount of withdrawn power [MW];
- $p_{downward}(\Delta t)$ prices of withdrawn energy [€/MWh].

The optimization model will have the final objective of evaluating the optimal management of the mobile storage system considering as an optimal criterion the maximization of the differential revenue (between the case study and the base case) of this car fleet, over a period of one year. It is clear that the sample of analysed data, on a year basis, could randomly not be indicative of the long-term average trend of the elements under examination. First of all because there is a real possibility, for example, to consider a year characterized by a trend in energy prices particularly advantageous, disadvantageous or otherwise unusual; above all since this case study has to be framed in a future scenario (where the spread of electric vehicles could be a massive phenomenon) in which energy authorities and markets could change the whole background.

That's why, in case of negative differential revenue, it will be possible to estimate, a posteriori, the different factors that can be modulated in order to promote the use of this technology.

3.5.2. Decision variables

Variables are those physical quantities that the optimization solver varies according to more or less refined algorithms in order to, generally speaking, minimize (in this case maximize) the objective function. Once arrived at a sufficiently accurate solution, according to the limits provided to the algorithm, the numerical values properly assigned to the variables are to be considered as the final results as much as the value assumed by the objective function. The interface functions allow to define the variables indicating their nature (continuous or binary) and setting their dimensions.

- Power offer per quarter of an hour fed into the grid [MWh],
  $\boldsymbol{P_{upward}(\Delta t)} \in \boldsymbol{[}\, x_{offer}\, ; \boldsymbol{P_{upward,max}}\boldsymbol{]}$:

  The model returns a vector of amount of power, to be offered according to the availability of vehicles and the pilot project's requests, which can only assume positive values.

- Power offer per quarter of an hour taken from the grid [MWh],
  $\boldsymbol{P_{downward}(\Delta t)} \in \boldsymbol{[}-\boldsymbol{P_{downward,max}}\, ; -x_{offer}]$:

  The model returns a vector of amount of power, to be retrieved according to the availability of vehicles and the pilot project's requests, which can only assume negative values.

- Auxiliary variable linked to outbound power $\boldsymbol{\delta_{upward}(\Delta t)} \in [\boldsymbol{0}, \boldsymbol{1}]$:

  The model returns a binary vector, depending on the aforementioned power variable, which can only assume value equal to 1 in case of upward offer, otherwise equal to 0.

- Auxiliary variable linked to inbound power $\boldsymbol{\delta_{downward}(\Delta t)} \in [\boldsymbol{0}, \boldsymbol{1}]$:

  The model returns a binary vector, depending on the aforementioned power variable, which can only assume value equal to 1 in case of downward offer, otherwise equal to 0.

The introduction of these auxiliary variables, namely the presence of both continuous and integer variables, inscribes the problem inside the set of MILPs.

3.5.3. Constraints

Constraints are the set of mathematical equations and inequalities that link together the variables of the model and mutually limit the range of variability.

- **Energy technical constraints**

1. $E(\Delta t_{final}) \geq E_{baseline}(\Delta t_{final})$;

The total amount of the aggregate energy E , involving the one used for charging vehicles as well as for services, has to be, in the last time step, at least equal to $E_{baseline}$, that employed for the charge only.

2. $E(\Delta t_{starting}) \leq E(\Delta t_{final}) \leq E(\Delta t_{final})$;

This quantity must also be, at any time, between $E(\Delta t_{starting})$, the amount of charge stored by all the vehicles at the starting time interval, and $E(\Delta t_{final})$, the one finally obtained.

The aforementioned variables have been obtained as shown below (n_{EVs} stands for the number of present EVs).

$$E = E(\Delta t_{starting}) + \int P_{total}\, dt$$

$$P_{total} = P_{baseline} + P_{upward} + P_{downward}$$

$$E(\Delta t_{starting}) = E_{max} \cdot SoC_{starting} \cdot n_{EVs}$$

$$E(\Delta t_{final}) = E_{max} \cdot SoC_{final} \cdot n_{EVs}$$

- **Power technical constraint**

3. $P_{charging}(\Delta t) \leq P_{total}(\Delta t) \leq P_{discharging}(\Delta t)$;

In order to define the power limits for P_{total}, previously explicited, it is necessary to take into account the available power instant by instant in the car fleet, defined as follows ($n_{c.s.}$ stands for the number of present charging station):

$$P_{charging}(\Delta t) = -\min[n_{EVs}(\Delta t), n_{c.s.}] \cdot P_{c.s.} = -P_{discharging}(\Delta t)$$

i.e. the available power depends on the power of each charging station, $P_{c.s.}$, times the minimum number between present EVs and the installed charging stations (with the hypothesis that one station can charge one car at a time).

- **Offer constraints**

4. $P_{upward}(\Delta t) \geq 0$;
5. $P_{downward}(\Delta t) \leq 0$;

Initially, the supply of power was separated into positive and negative so as to have two different variables for upward and downward services respectively. In order to establish a supply strategy discretized in 15 minutes, it is necessary to introduce two binary variables, δ_{upward} and $\delta_{downward}$, specifying whether or not one of the two offers is present. The following constraint in fact specifies that it is impossible for the two bids to be submitted at the same time.

6. $\delta_{upward}(\Delta t) + \delta_{downward}(\Delta t) \leq 1$;

In the modelling phase, the introduction of binary variables guarantees a great deal of flexibility but at the expense of the ease of solution. Indeed their value is unknown and depends on the choice of the power exchanged with the grid. The choice of having two different variables for selling and buying power, and their associated binary vectors, has been useful for a first naïve approach in which P_{upward} and $P_{downward}$ have been considered equal to the threshold x_{offer} ; even if both integer and continuous variables are present, namely the considered problem is a MILP, P_{total} exchanged with the grid, and therefore the objective function too, can be expressed simply as the product between binary variables and constant values.

In order to specify the minimum offer to be respected, in both cases, for participation in Terna's pilot project, it is necessary to remind that a certain minimum threshold x_{offer} , expressed in MW, has to be reached and therefore that

7. $\delta_{upward} = 1 \leftrightarrow P_{upward} \geq x_{offer}$;
8. $\delta_{downward} = 1 \leftrightarrow P_{downward} \leq -x_{offer}$;

It’s undeniable that this logical constraint has to be translated in one readable for the interface. Once the requirement has been formulated in a logical proposition, it is possible to automatically translate it into mixed-integer linear constraints using known rules [8].

This set of rules, the so-called Big-M technique, is a technique that allows, among other things, to translate logical relations into bonds of inequality. According to one of the general rule:

$$\delta = 1 \leftrightarrow f(x) \geq 0$$

it is equivalent to this set of mixed-integer linear inequalities

$$f(x) \geq m - m \cdot \delta$$

$$f(x) \leq M$$

where $m = \min_x f(x)$ and $M = \max_x f(x)$

If M and m are properly chosen, these constraints are trivially satisfied. In computational terms, and also to avoid bad conditioning of the problem, it is advantageous to be able to have the most accurate possible estimate of the maximum and minimum points of $f(x)$. Through this variables introduction, the objective function has been transformed in a non linear product; the product of binary variables with continuous variables can also be rewritten through big-M technique in the form of whole mixed linear constraints. Even in this case, following the general rule,

$$z = f(x) \cdot \delta$$

Converted into

$z \leq \delta \cdot M$

$$z \geq \delta \cdot m$$

$$z \leq f(x) - (1 - \delta) \cdot m$$

$$z \geq f(x) - (1 - \delta) \cdot M$$

Particularly, in the case study, z results from the product of $f(x)$, amount of P_{upward} ($P_{downward}$), and the binary variables ∂_{upward} (∂_{upward}); constraint number 7. , referred to $P_{upward} = x_{offer} \cdot \partial_{upward}$, can be therefore rewritten as follows, only using the large positive penalty constant M.

$$P_{upward} \leq \delta_{upward} \cdot M$$

$$P_{upward} \geq -\delta_{upward} \cdot M$$

$$P_{upward} \leq x_{offer} + \left(1 - \delta_{upward}\right) \cdot M$$

$$P_{upward} \geq x_{offer} - (1 - \delta_{upward}) \cdot M$$

The compliance with the logical relations can be easily verified:

If $\delta_{upward} = 0 \rightarrow 0 \leq P_{upward} \leq 0$ or $x_{offer} - M \leq P_{upward} \leq x_{offer} + M$ (trivial);

If $\delta_{upward} = 1 \rightarrow -M \leq P_{upward} \leq +M$ (trivial) or $x_{offer} \leq P_{upward} \leq x_{offer}$.

The same applies for constraint number 8.

9. $P_{upward}(\Delta t_i) \geq P_{upward}(\Delta t_i - n) - P_{upward}(\Delta t_i - N)$;
10. $P_{downward}(\Delta t_i) \leq P_{downward}(\Delta t_i - n) - P_{downward}(\Delta t_i - N)$;

Another important specification to be respected, which is present in both regulations discussed, is the minimum duration t_{min} of availability for dispatching services.

In the case of participation in UVAM, the latter must be equal to 2 hours; in the case of UVAR, the minimum duration is to be considered reduced and more flexible than in the first case and, since it has not been declared within the deliberation, it has been assumed to be equal to 1 hour. Therefore, the constraints expressed above constitute a series of systems of inequalities in which $T = 96$, $i = 1, \dots, T$, $N = \frac{t_{min}}{\Delta t}$, $n = 1, \dots, N$.

Developing the series for a specific Δt_i, indiscriminately for one of the two constraints, the following system can be obtained:

$$\begin{cases} P_{upward}(\Delta t_i) \geq P_{upward}(\Delta t_i - 1) - P_{upward}(\Delta t_i - N) \\ P_{upward}(\Delta t_i) \geq P_{upward}(\Delta t_i - 2) - P_{upward}(\Delta t_i - N) \\ \qquad\qquad\qquad\qquad \dots \\ P_{upward}(\Delta t_i) \geq P_{upward}(\Delta t_i - N) - P_{upward}(\Delta t_i - N) \end{cases}$$

In other words, for each time interval the amount of selling power must be at least equal to or greater than the amount offered in the immediately preceding interval and up to the previous eighth interval (in the case of UVAM, otherwise fourth interval).

The same applies for the downward power, remembering that, since it is conventionally a negative quantity, the offered power has to be always minor or equal.

Even if at first sight the number of decision variables seems to be a limited number compared to the constants, it should be remembered that in the case of quarter-of-an-hour variables, YALMIP and CPLEX are dealing with vectors of 25632 numbers (267 considered days), consequently the overall account amounts to tens of thousands of values to be optimized.

3.6. Disaggregated model

To make the problem as general as possible, it is possible to reformulate it by specifying different technical characteristics for each battery, thus being able to analyse and evaluate the behaviour of each individual vehicle, and thus to obtain more specific results. Therefore below it is presented a disaggregated model (i.e. referred to each user) that, despite the above mentioned advantages, was finally decided not to use, considering unnecessary a greater computational burden in order to obtain technical results of little interest, especially in the light of the case study in examination in which the aggregator acts as a central and essential figure of the unit. However, by shifting the focus of interest, it may be useful to obtain an individual optimization of the variables at stake in order to establish a more accurate and fair division between users, by the BSP, of costs and profits.

Input data are the same except for the starting assumptions made for energy and power baselines computation.

- **Battery capacity** for each vehicle: uniform distribution between 40 – 80 kWh
- **Initial state of charge** of each EV ($SoC_{starting}$): uniform distribution between 0.4 and 0.8 p.u.

In this case, the calculation of the energy absorbed by each vehicle to allow the achievement of the target, that is, even in the disaggregated model, a SoC_{final} equal to 0.9 p.u., is carried out considering the possibility that, due to a short stay time $\sum \Delta t_{EV,i}$ of a vehicle, the power required for recharging using the FCFS algorithm (constant power during the entire stay) does not allow this target to be reached. In this case, the vehicle recharging power $P_{EV,i}$ would be limited to the charging station $P_{c.s.}$ thus reaching a state of charge equal to

$$SoC(\Delta t_{final})_{EV,i} = SoC(\Delta t_{starting})_{EV,i} + \frac{P_{EV,i} \cdot \sum \Delta t_{EV,i}}{E_{max_{EV,i}}}$$

Following the same reasoning and procedure previously described in paragraph 3.3, $P_{baseline}$ and $E_{baseline}$ can be obtained no more as referred to the whole aggregate but as matrices in which each column represents each vehicle: “disaggregated” quantities are therefore available every fifteen minutes.

The total power, and other linked quantities, is rewritten as follows.

$$P_{total} = \sum_i (P_{aux,i} + P_{baseline,i})$$

3.6.1 Decision variables

Focusing into the actual optimization problem, a new variable is used to replace P_{upward} and $P_{downward}$.

- Power per quarter of an hour fed or injected into the grid [MWh],

  $\boldsymbol{P_{aux}(\Delta t)} \in \boldsymbol{[P_{downward,min}}\,; -\boldsymbol{x_{offer}}\,] \cup [\,\boldsymbol{x_{offer}}; \boldsymbol{P_{upward,max}]}$:

  The model returns a matrix of amount of "auxiliary" power, dimensionally [time x vehicles], to be offered according to the availability of vehicles and the pilot project's requests, which can assume both positive and negative values.

- $\boldsymbol{\delta_{upward}}(\Delta \boldsymbol{t}) \in [\boldsymbol{0}, \boldsymbol{1}]$;
- $\boldsymbol{\delta_{downward}}(\Delta \boldsymbol{t}) \in [\boldsymbol{0}, \boldsymbol{1}]$.

For simplicity sake, the two binary variables are defined as already seen in 3.4.2; alternatively, a unique variable $\delta_{auxiliary}$ could have been used. It is also observed that, since the objective function is again the sum in time of convex functions, the problem can be rewritten without the use of any binary variable using the epigraphic form. Hence, reformulating the canonical form of a general non-linear problem

$$\min_{x} J(x)$$

$$h(x) \geq 0$$

$$g(x) = 0$$

in the equivalent epigraphic form, the previous objective function is expressed as a constraint.

$$\min_{x,t} t$$

$$J(x) \leq t$$

$$h(x) \geq 0$$

$$g(x) = 0$$

In this way objective functions and convex linear constraints (f.i. the maximum of linear functions is a piecewise linear convex function) are therefore generally rewritable as linear constraints. The number of tracts is equal to the number of constraints and, depending on the case, one of the two constraints is activated to obtain an effect equivalent to that of the binary variables.

3.6.2 Constraints

Compared to the case analysed, further constraints must be considered taking into account both the behaviour of the aggregate and that of individual vehicles. As far as energy constraints are concerned, they are only an extension of the basic case, while the main differences are to be found in the technical constraints of the power supply.

- **Energy technical constraints**

1. $E_{total,i}(\Delta t_{final}) \geq E_{baseline,i}(\Delta t_{final})$;
2. $E_i(\Delta t_{starting}) \leq E_{total,i}(\Delta t) \leq E_i(\Delta t_{final})$;

Both equivalent to the constraints of paragraph 3.4.3 but referring to each unit.

3. $0 \leq E_i(\Delta t) \leq E_{max,i}$;

The energy stored by each battery must respect its own physical constraints, depending on the capacity of each battery.

- **Power technical constraint**

4. $-P_{c.s.} - P_{baseline,i}(\Delta t) \leq P_{aux,i}(\Delta t) \leq P_{c.s.} - P_{baseline,i}(\Delta t)$;

The power offer of a single vehicle is limited by the power available for each vehicle, i.e. that of the charging station ($-P_{c.s.} \leq P_i(\Delta t) \leq +P_{c.s.}$).

- **Offer constraints**

5. $x_{offer} - \sum_i P_{aux,i} \leq M - M \cdot \delta_{upward}$;

It represents the extended version of the upward minimum offer constraint and translate the logical proposition “ $\delta_{upward} = 1 \rightarrow x_{offer} - \sum_i P_{aux,i} \leq 0$”.

6. $-x_{offer} + \sum_i P_{aux,i} \leq M - M \cdot \delta_{downward}$;

It represents the extended version of the downward minimum offer constraint and translate the logical proposition " $\delta_{downward} = 1 \rightarrow x_{offer} + \sum_i P_{aux,i} \leq 0$".

7. $-P_{aux,i} \leq M - M \cdot \delta_{upward}$;

It specifies that, if the aggregate offer is positive, every vehicle participating in it has to follow the same trend i.e. $\delta_{upward} = 1 \rightarrow -P_{aux,i} \leq 0$.

8. $P_{aux,i} \leq M - M \cdot \delta_{downward}$;

It specifies that, if the aggregate offer is negative, every vehicle participating in it has to follow the same trend i.e. $\delta_{downward} = 1 \rightarrow P_{aux,i} \leq 0$.

9. $P_{aux,i} \leq M \cdot \delta_{upward}$;
10. $P_{aux,i} \geq M \cdot \delta_{downward}$;

Other two inequalities formalize that every element of the auxiliary power matrix has to be null in case of offer absence ($\delta_{upward} + \delta_{downward} = 0 \rightarrow P_{aux,i} = 0$).

11. $\delta_{upward}(\Delta t) + \delta_{downward}(\Delta t) \leq 1$;
12. Related to $P_{upward} = \sum_i P_{aux,i} \cdot \delta_{upward}$;
13. Related to $P_{downward} = \sum_i P_{aux,i} \cdot \delta_{downward}$;
14. $P_{upward}(\Delta t_i) \geq P_{upward}(\Delta t_i - n) - P_{upward}(\Delta t_i - N)$;
15. $P_{downward}(\Delta t_i) \leq P_{downward}(\Delta t_i - n) - P_{downward}(\Delta t_i - N)$.

As for the last constraints, no comments are needed because of the totally equivalence with respect to paragraph 3.4.3.

4. Results analysis

The optimization model has been thought to be very flexible. Results are extremely sensitive to initial assumptions and conditions; according to combination of data input and parameters, the solver provides quite different solutions. In this way it is possible to analyse several different scenarios and identify the most advantageous conditions for the success of V2G technology. In fact, the problem can be formally defined as deterministic - in the modelling phase every aspect is known a priori and in any case it is assumed as devoid of uncertainty.

This last chapter presents and critically analyses the results of the different optimization iterations. Initially, considering a time frame of one working day as an example, the actual behaviour of the fleet every fifteen minutes is depicted to identify the actual impact, at the operational level, of enabling market services. The perspective will then be broadened to observe the overall results over a larger sample of values, the entire annual time frame, so that a typical variability is incorporated into the analysis quantifying the possible benefits of this application.

4.1 Scenarios

The simulations, both on a daily and an annual time horizon, were conducted by inserting the subject of the study case in two different contexts, that is, in the two different pilot projects, introduced in chapter 2, promoted by the Italian TSO. The participation of the EVs aggregate in one project rather than the other determines a different behaviour both in terms of costs and in terms of market supply.

Focusing on the first option- in case of participation in UVAM - the aggregate must first submit a bid of at least 1 MW, with a duration of at least two hours.

On the other hand, in the case of participation in UVAR, designed specifically to encourage the use of electric vehicles for the provision of balancing services, the threshold is lowered to 0.2 MW with a minimum duration not strictly defined to be adapted to the needs of mobility. In order to standardise the scenario - and taking a precautionary measure - the threshold was chosen equal to one hour.

After the first results obtained, it was decided to explore another type of smart charging, so far not mentioned: the so-called V1G, i.e. unidirectional controlled charging. The latter technology allows electric vehicles to participate in the ASM without reversing the power flow i.e. working only in absorption. The offers to be considered in this case will always be upward and downward, with the difference that the behaviour of the vehicle is always as load and never as a generator, namely

$$\begin{cases} P_{upward}(\Delta t) \geq 0 \\ P_{downward}(\Delta t) \leq 0 \\ P_{baseline}(\Delta t) + P_{upward}(\Delta t) + P_{downward}(\Delta t) \leq 0 \end{cases} \qquad \forall \Delta t \in T$$

This solution also allows the realization of the service starting from the basic case of vehicles charging only, not providing in fact the installation of bi-directional charging stations essential for the V2G.

Finally, it should be stressed that the function to be maximised, and therefore the economic variables involved, has been defined with the participation in UVAM in mind; in the economic evaluation of the various options considered, this statement will be explained in detail.

4.2 Daily results

First of all, in order to report a qualitative analysis of the trend, in power and energy, of the aggregate, a working day of the winter season (8 January 2018) - the same that has been chosen for the input data visualization- as it has a standard turnout of vehicles and such as to be able to exemplify all year round.

The graphs below depict the four subcases introduced: V2G and V1G services provided in case of participation in UVAM or UVAR respectively.

4.2.1 V2G case: UVAM and UVAR context

As soon as the stationary point of the objective function has been reached, it is possible to go back to the numerical values of the decision variables involved in the optimal solution.

As regards the power exchange, the followings are reported in Figure 12:

- $P_{baseline}(\Delta t)$,
- $P_{upward}(\Delta t)$,
- $P_{downward}(\Delta t)$.

The charging profile, independent of the bids, is computed through the FCFS algorithm and using constant power, able to ensure the achievement of the target state of charge of each vehicle (total EVs of the day: 222).

As for the offers, the dispatching strategy adopted includes two takeover bids, carried out at the beginning and end of the stay of the vehicles, and two sale offers carried out during the hours of greatest presence of the vehicles, thus achieving in absolute value a greater power than the downward power.

It should be noted that the minimum duration of the offer of two hours is respected in both cases.

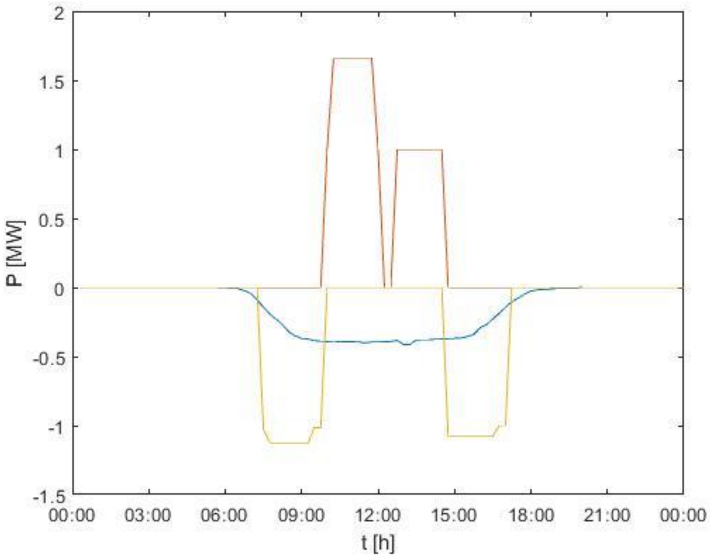

Figure 13 Bought and sold power with respect to the charging profile (V2G - UVAM).

The observance of the constraints is also confirmed in Figure 11: the final energy of the aggregate is that obtained by reaching the complete recharge of each vehicle. Moreover, the energy never falls below the total starting energy, ensuring that, even in the event that the vehicles should stop recharging before the scheduled time, the state of charge of the batteries is never lower than $SoC_{starting}$.

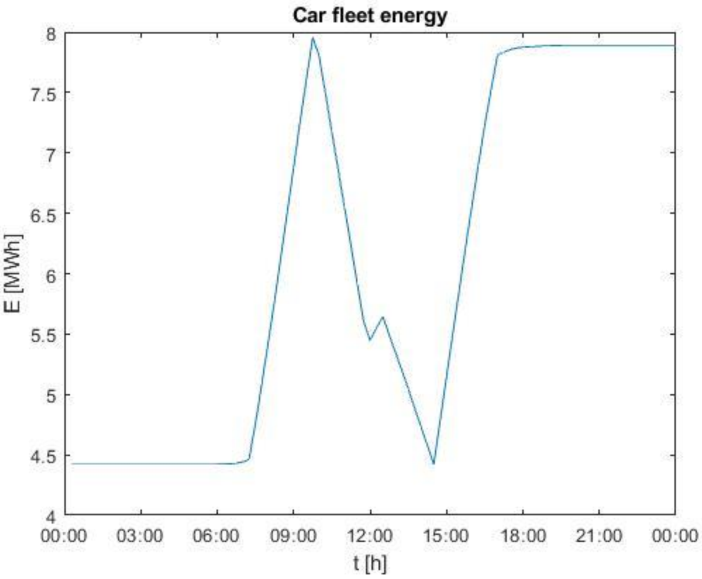

Figure 14 Energy trend of the aggregate (V2G - UVAM).

Continuing to consider the V2G technology, in view of the UVAR this time, it was chosen to simulate the behaviour of the aggregate with two different initial conditions, that is, a higher state of charge (which still guarantees a fair autonomy, about 45 km for EVs); it can be observed that in the previous case it would not have been possible to make this distinction because the minimum thresholds in power and duration wouldn't have allowed any supply strategy.

I. Average $SoC_{starting} = 0.5$:

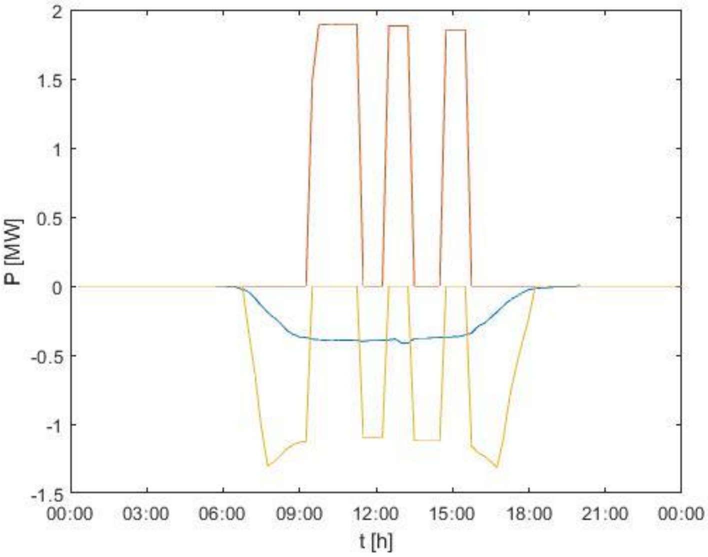

Figure 15 Bought and sold power with respect to the charging profile (V2G - UVAR, I)

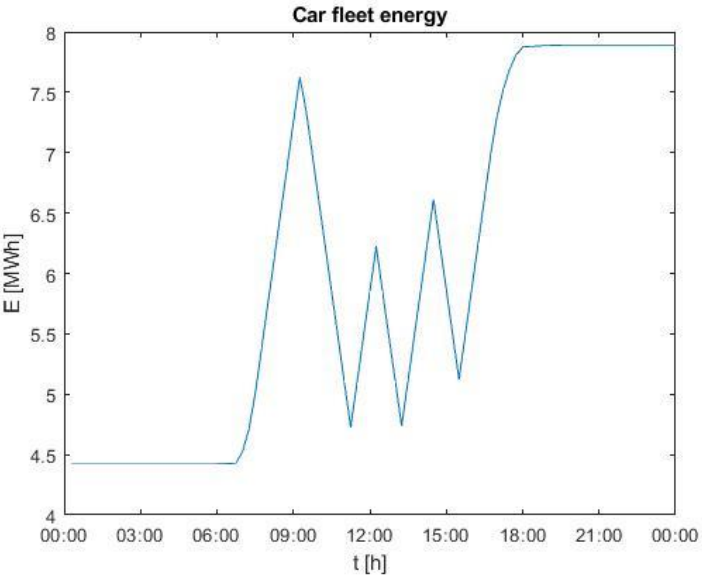

Figure 16 Energy trend of the aggregate (V2G - UVAR, I).

Compared to participation in UVAM, it is clear from Figure 12 that the number of upward and downward offers is greater thanks to the lower strictness of the constraints. Intuitively, this allows us to assume that we have greater economic benefits.

II. Average $SoC_{starting} = 0.7$:

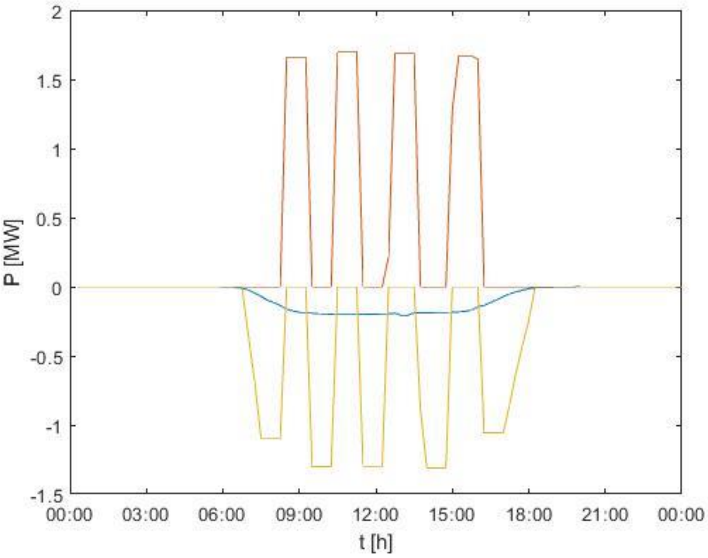

Figure 17 Bought and sold power with respect to the charging profile (V2G - UVAR,II).

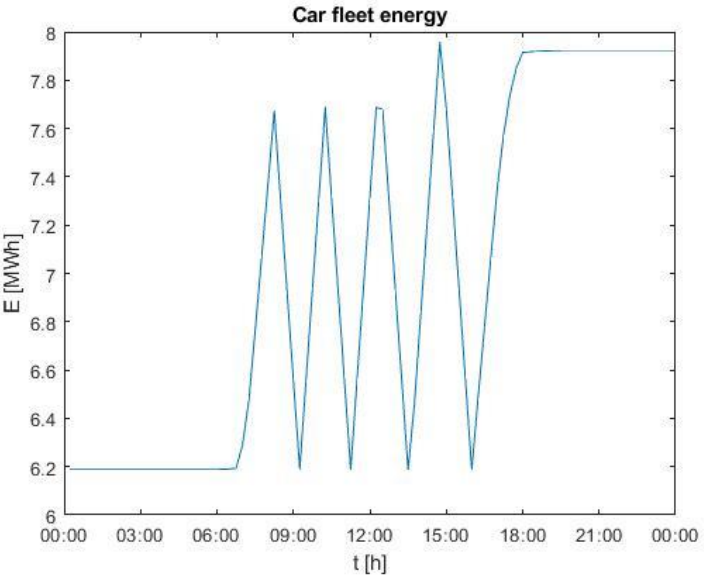

Figure 18 Energy trend of the aggregate (V2G - UVAR, II).

Figure 14 and, above all, Figure 15 show how the up and downs on energy trends involve multiple charge and discharge cycles compared to the absence of services. In any case, in order to protect EVs holders, ARERA is required to define to UVAM and UVAR operators the timing and methods for providing vehicle owners with information on the actual use of batteries.

4.2.2 V1G case: UVAM and UVAR context

When the charging infrastructure allows only to withdraw from the network, therefore in V1G mode, participation in UVAM is excluded: as we can easily guess, the solver cannot complete any successful iteration, as the impossibility of bidirectionality does not allow the fulfilment of the requirements of the above unit.

The characteristics of a UVAR, on the other hand, seem to fit perfectly with the V1G recharge. Figure 16 also shows a similar trend to the previous ones in terms of order and sequentiality of bids; this does not apply to P_{upward}, which can no longer be defined as sale offer because the aggregate isn't allowed to operate as generator. This now corresponds almost to the total cancellation of the charging profile.

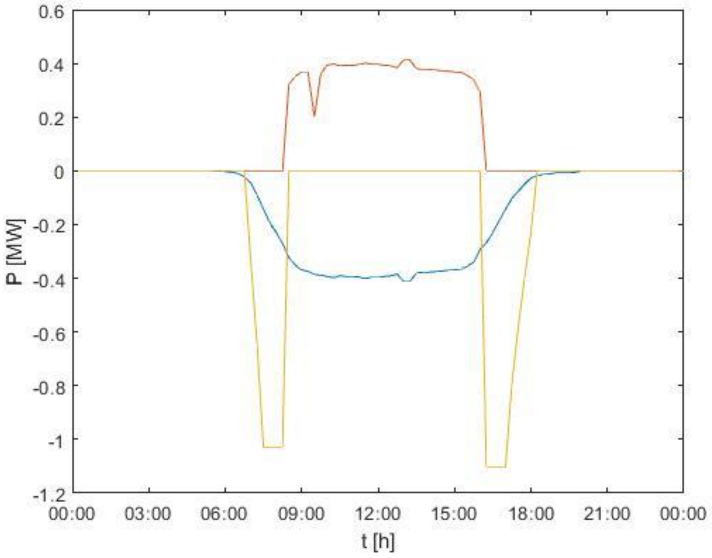

Figure 19 Bought and sold power with respect to the charging profile (V1G - UVAR).

The stepwise energy performance of the car fleet shows that the V1G charging mode simply corresponds to adjusting the rate of charging, without further deterioration of the batteries.

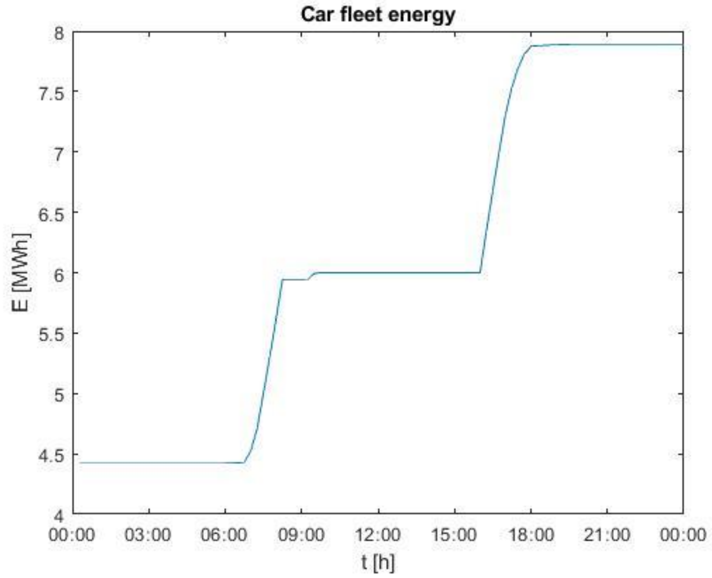

Figure 20 Energy trend of the aggregate (V1G - UVAR).

4.3 Annual results

After showing a purely qualitative analysis, we report the perspective extended to the entire time horizon where the observation is focused on the various energy quantities involved at a cumulative annual and monthly level. These values can be useful in order to evaluate the participation of a mobile storage system of this entity (car fleet with a maximum number of EVs equal to 300) in combination with generation plants for example, as required by the UVAM, or alternatively only for ancillary services to the network.

It is very interesting to compare the different scenarios from the point of view of the power offered, representing them in aggregate form to have an idea of frequency, duration and amplitude of the data.

4.3.1 Exchanged energy

Figures 18, Figures 19 and Figures 20 show the results in the same order as paragraphs 4.2.1 and 4.2.2.

In each of the three bar charts it has been chosen to visualize, even if it is clear that the two quantities coincide in every case, both the quantity of energy injected and in withdrawal, in order to keep in mind the bidirectionality of the energy flows.

As one might expect, as regards the V2G mode, the effect of the regulation hypothesis under consideration is not substantially different to that of the previous deliberation. Surely, in the case of UVAM the entities involved are smaller: on a monthly basis, the minimum energy offered in module goes from 40 MWh to the maximum of 111 MWh. The range variability is quite significant; the case limit of August stands out in which the energy needed for the baseline exceeds that on offer.

The variability is lessened in the case of UVAR, where there is a minimum monthly energy of 125 MWh compared to the maximum of 150 MWh. In this case, August is no longer an outlier, where the lower inflow of EVs still allows to offer power within the thresholds set by the hypothesis assumed.

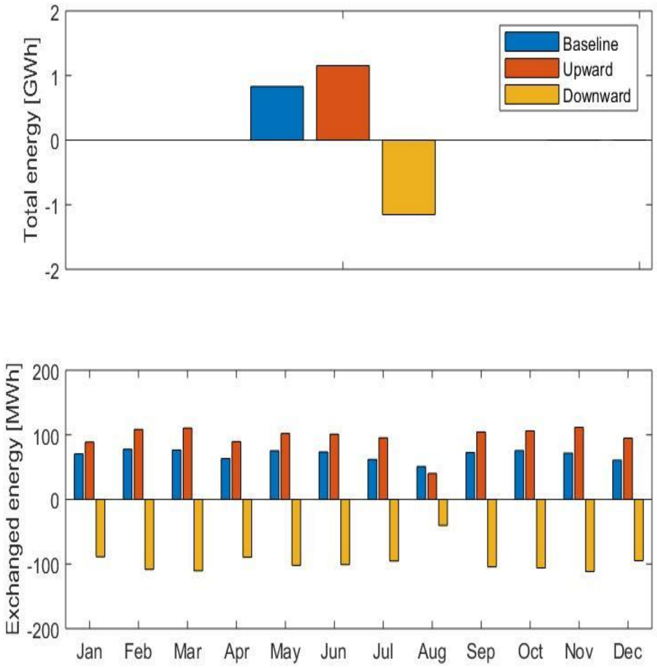

Figure 21 Upward and downward energy with respect to the baseline (V2G - UVAM).

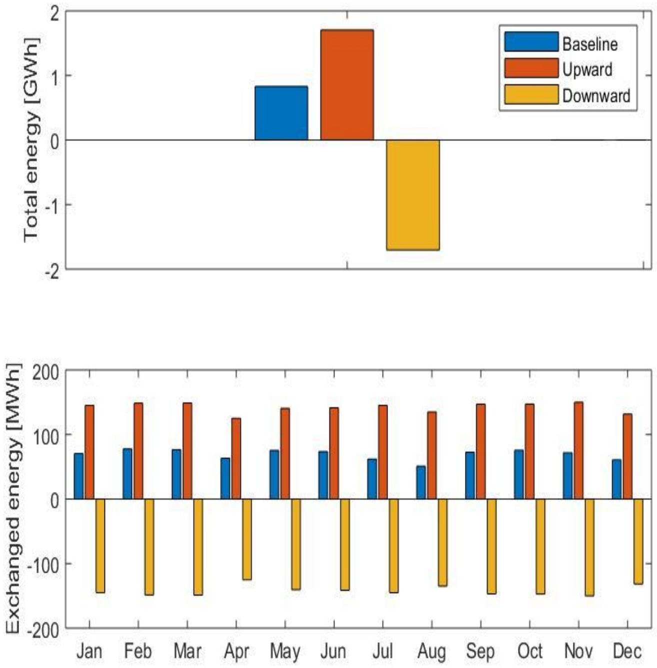

Figure 22 Upward and downward energy with respect to the baseline (V2G - UVAR).

Finally, the figures involved in v1G charging are decidedly lower, of course always lower than the baseline, with 36 MWh and 60 MWh as minimum and maximum.

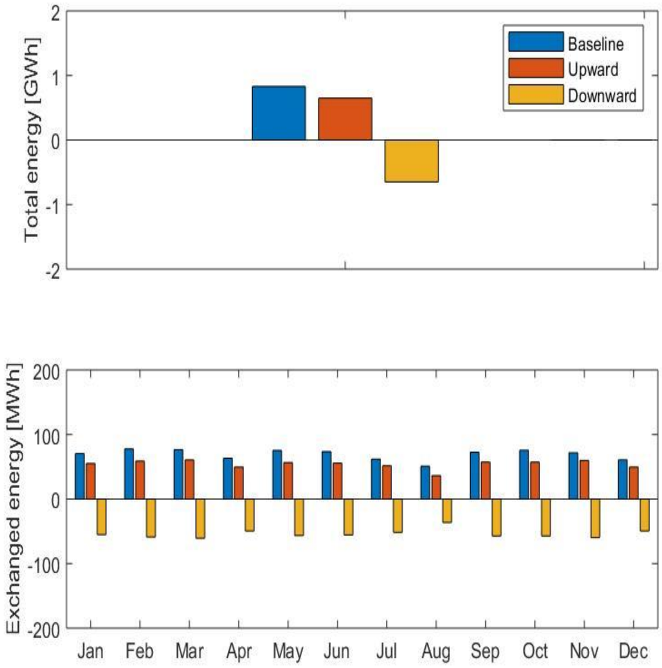

Figure 23 Upward and downward energy with respect to the baseline (V1G - UVAR).

By the way, the energy exchanged reported likely does not correspond, in the case of the above studies, to the energy needed by the grid to fill any imbalances. This conduct is caused by the search for an economic maximization, as well as, in the case of V1G, by the ability to work only in absorption. In other words, in mixed virtual units with RES as generation units, the V2G solution could be structured to meet mainly the needs of the grid or of the unit, while the V1G case, as it is structured (unidirectional charging stations), can do nothing to contain the phenomenon of negative imbalance caused by the random lack of any renewable sources included in the unit.

4.3.2 Power offers

As already specified, the modulating power to be presented on ASM, must exceed a certain threshold with decimal progression. For this reason, the frequencies of the offers have been reported, intended as duration in hours, according to the discrete power values grouped with a decimal binning starting from the threshold value.

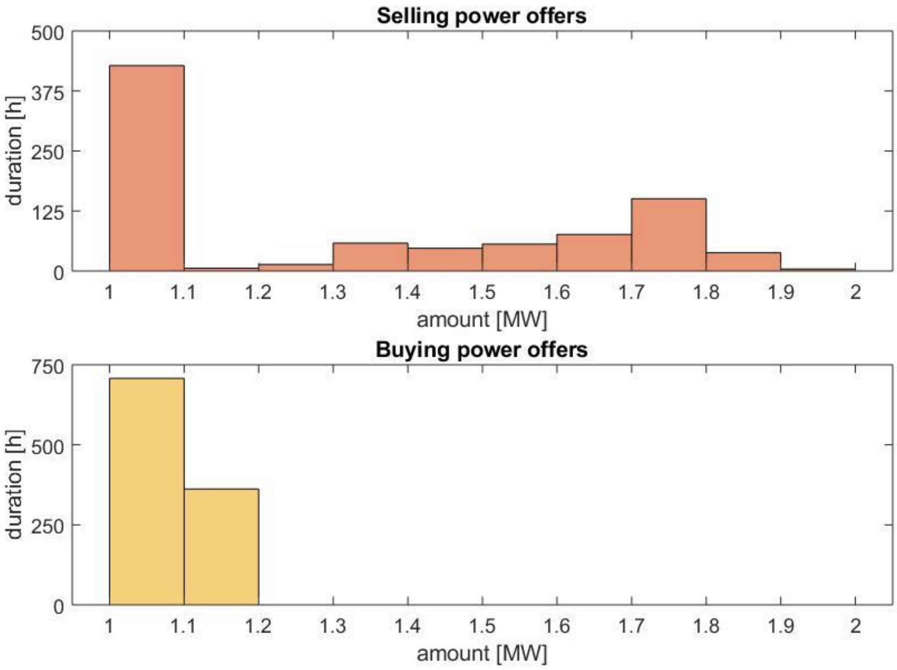

Figure 24 Power offers distributions (V2G - UVAM).

In both V2G scenarios, i.e. for Figures 21 and 22, it seems that optimisation tends to make upward offers with more amplitude power than downward bids; profit maximization justifies these distributions.

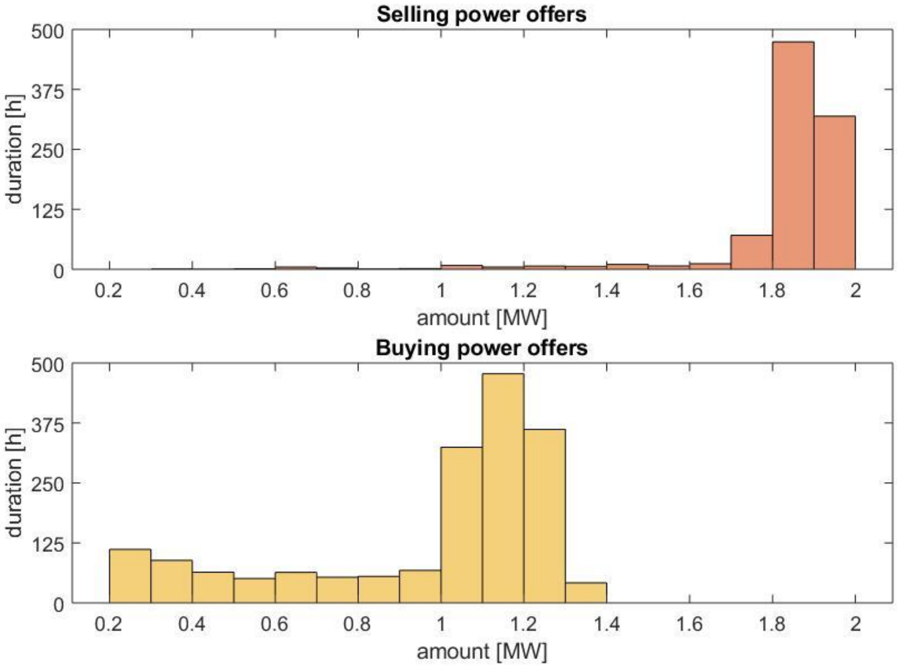

Figure 25 Power offers distributions (V2G - UVAR).

Figure 23, on the other hand, shows the opposite; clearly the sale offers are limited by the unidirectionality of the smart charging mode.

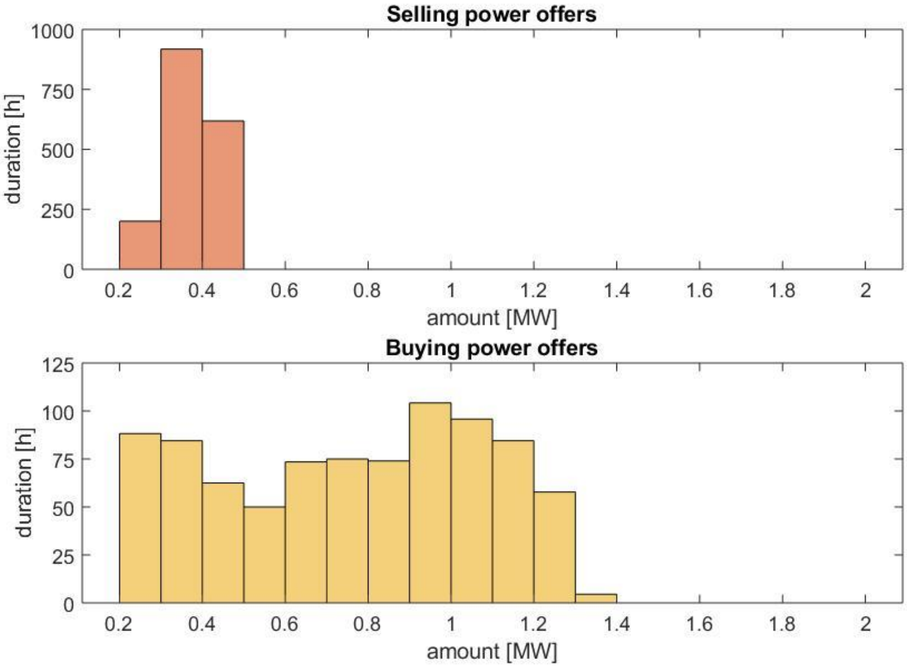

Figure 26 Power offers distributions (V1G - UVAR).

4.4 Economic assessments

First of all it's useful to identify the economic conditions for which an initial investment is justified for the installation of the necessary infrastructure for the V2G, i.e. bidirectional charging stations in place of those currently used for charging only (suitable instead for the V1G technology).

The basic parameters influencing the economic return for the considered case study are

- accepted sale and purchase price [€/MWh] for the ancillary services,
- energy cost on the day-ahead EM for EVs recharging,
- system charges and transmission and distribution costs associated with the energy withdrawn,
- excise duties and VAT [10],
- cost for batteries deterioration, as explained below.

Of course, this last cost item can only be estimated and deduced; the simple reasoning behind this estimate has considered average values of $cost_{battery}$ and of n_{cycles} , respectively the batteries price based on capacity and the number of cycles, i.e. $cost_{battery} = 200\ €/kWh,\ n_{cycles}$ = 4000 such that

$$cost_{battery\,wear} = \frac{cost_{battery}}{n_{cycles}} = 0.05\ \left[\frac{€}{kWh \cdot cycle}\right]$$

It has to be underlined that not all the constants of the economic analysis have been included in the expression of the objective function, i.e. the overall economic evaluations have been carried out after the execution of the dispatching algorithm for each case study. However, it is necessary to remember that, as far as the charges are concerned (their components are explicit in Table 2),

- in UVAM pilot project, they have to be included both in upward and downward offers;
- in UVAR pilot project, variable components of system charges and network rates do not apply for withdrawals.

Therefore, since the charges are applied to the decisional variables likewise for sale offers and takeover bids, and since the additional parameters to be included in the evaluation are constant and do not influence the maximization of the objective function, the optimized case is to be identified with the case of participation in UVAM.

Finally, the components relating to dispatching costs are those that apply to the protected market.

Table 2 Variable components of system, network and dispatching charges. [10]

Components	**€/MWh**
System charges	50,85
Network charges	8,46
Dispatching charges	11,55
Other dispatching charges	4,02
Total charges	74,877
Network and system charges	59,31

As already said, the capacity remuneration, an additional facility for participating in mixed units, has not been considered. This remuneration corresponds to

30 k€/year/MW for offers of at least 2 hours, during the time slot between 2 and 8 pm, on weekdays. In the event of request, however, the price of offers on ASM must not exceed a strike price, updated to 2018, equal to 400 €/MWh [8]. The decision to neglect this incentive is explained by the fact that it will likely disappear with the more and more spread of mixed units compared to other traditional plants.

On the other hand, every power offers, defined as decisional variables by the optimization model, are reasonably considered as accepted: in fact the prices assumed are underestimated with respect to the range of average prices accepted.

After a brief explanation of all the cost items used and the justification of the hypothesised values, the core of actual analysis can be investigated. The latter has been focused on the simulation of the total costs to be incurred on the basis of the possible provision of services V2G or V1G, participating in UVAM or UVAR. Instead of applying the rates for each option on the basis of the pilot project to which it belongs, a distinction was made on the basis of the different rates to be applied in each case in order to have a broader range of possible solutions. At the end of the analysis, it will be shown which cost policy is currently applied to the three scenarios under examination discussed in paragraph 4.1.

The distinction between charges implemented provides for the following cases

I. **Baseline**: the option where no services are provided to the ASM, thus including only the costs related to EVs recharging;
II. **Total charges**: all components of the charges, to both types of offers, are applied;
III. **Partial downward charges**: in the case of withdrawal offers, only part of the costs is applied i.e. everything except for system and network charges.

In more detail, the total costs for the above cases in the annual fleet simulation were expressed as follows

I. $cost_I = [E_{base} \cdot (p_{EM} + p_{charges,tot} + p_{excises})] \cdot (1 + VAT)$

II. $\forall E_{sell}(\Delta t) : E_{sell}(\Delta t) > | E_{base}(\Delta t)| + |E_{buy}(\Delta t)|$

$$cost_{II} = -(E_{sell} \cdot p_{AMS,sell})$$

$$\forall\, E_{sell}(\Delta t) : \; E_{sell}(\Delta t) \leq |\, E_{base}(\Delta t)| + |E_{buy}(\Delta t)|$$

$$cost_{II} = -(E_{sell} \cdot p_{AMS,sell}) + \\ [E_{buy} \cdot (p_{AMS,buy} + p_{charges,tot} + p_{excises} + cost_{b.w.}) + \\ \big((E_{base} - E_{sell}) \cdot (p_{EM} + p_{charges,tot} + p_{excises})\big)] \cdot (1 + VAT)$$

III. $cost_{III} = cost_{II} + \sum_i E_{buy,i} \cdot \Delta t \cdot p_{charges}$

With

- $p_{excises} = 12{,}5\ [€/MWh]$;
- $VAT = 0.22$;
- $p_{charges,tot}$, total amount of charges $[€/MWh]$;
- $p_{charges}$, system and network charges $[€/MWh]$;
- $cost_{b.w.}$, cost of batteries wear $[€/kWh]$;
- p_{EM}, day-ahead EM price in F1 time zone $[€/MWh]$;
- $p_{AMS,buy}$, upward accepted price $[€/MWh]$;
- $p_{AMS,sell}$, downward accepted price $[€/MWh]$.

E_{sell}, E_{base}, E_{buy} corresponds to E_{upward}, $E_{baseline}$, $E_{downward}$ of previous paragraphs.

First of all, in order to compare the two options of service provision with the case of recharging only, which does not foresee any gain, it was chosen to calculate the costs of the three scenarios considering them as a positive quantity. All the other variables of the expressions are considered in absolute value.

In this way, in case I the energy of recharge is weighted by the price at which you buy on EM including all charges, excise duties, and the percentage of VAT applied.

Option II provides for a distinction according to the behaviour of the park as a generator, if the injected energy exceeds the input, otherwise as a load. In the first case, the costs are translated into profit from the sale of energy, to which no charges apply. In the second case, there are three terms: the first corresponds to the aforementioned gain; the other two, to which VAT is applied, consider the cost of the energy purchased, including charges and excise duties, and to which is associated the estimated cost of wear batteries per unit of energy, as well as the costs of the baseline net of upward energy.

Having said that, Figures 24, 25 and 26 finally show the daily cost trends in the three scenarios analysed so far; in each of them are distinguished the cases II and III of pricing.

In all three figures the monthly cost trend does not has large variations, except for the collapse of costs in August; the explanation is to be found in the lower turnout of employees in that period. In addition, there are points where costs are almost zero since the weekdays also include some holidays during which the number of vehicles is less than ten. The choice of not deleting this small percentage of outliers was made to take into account also the effect of days when participation in ASM is not possible.

The arrangement of the baseline cost compared to cases II and III in V1G graph is quite different from the two previous ones, as will be clearer from the numerical values reported in the tables.

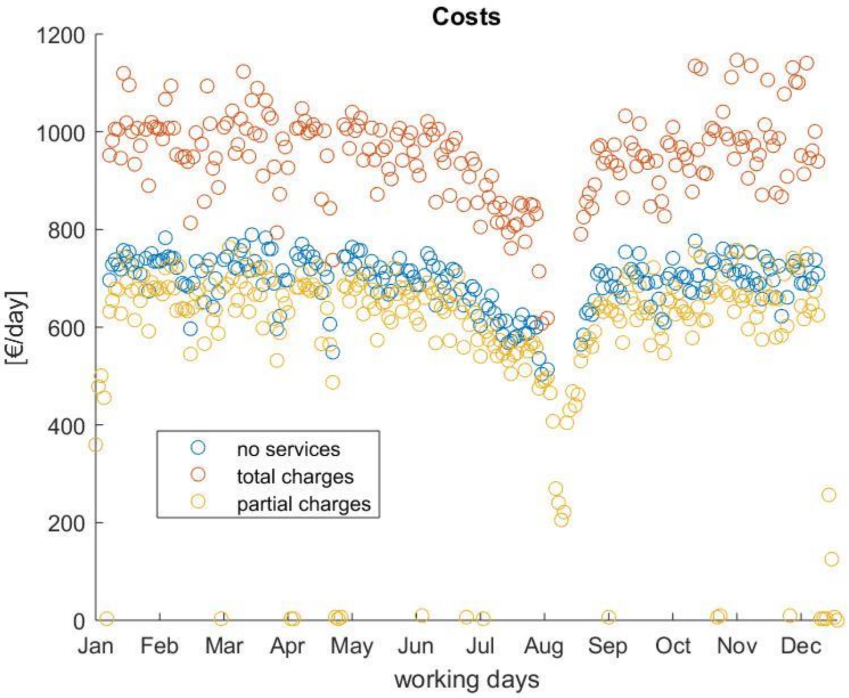

Figure 27 Costs annual trend (V2G - UVAM).

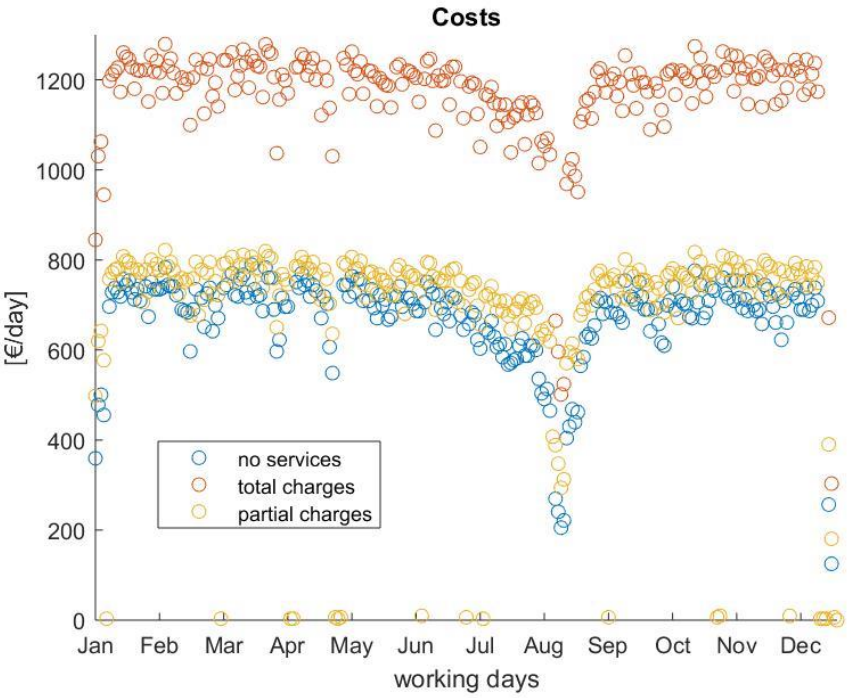

Figure 28 Costs annual trend (V2G - UVAR).

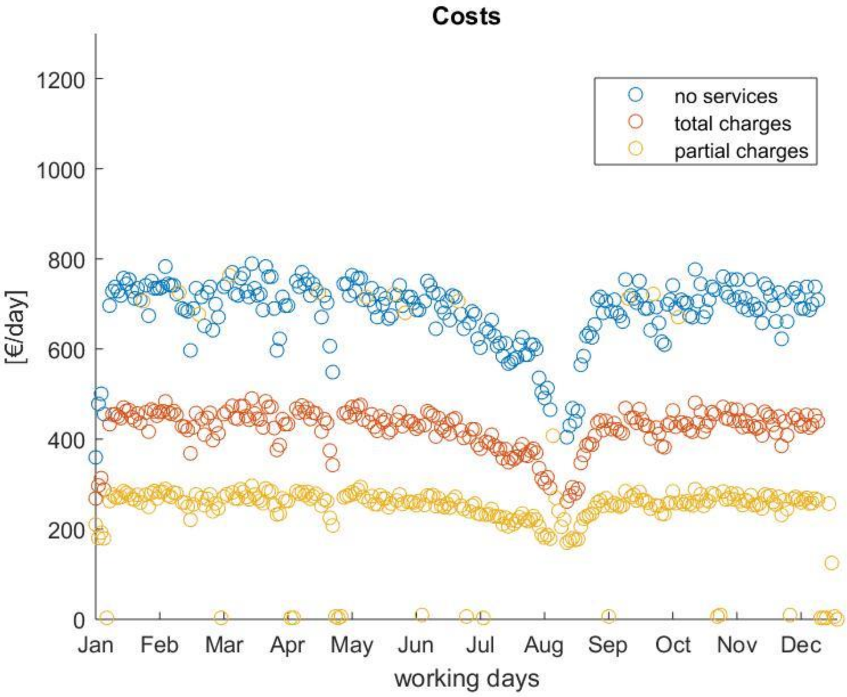

Figure 29 Costs annual trend (V1G - UVAR).

Table 3 and Table 4 show economic results, both in absolute and relative terms, computed obtained with economic variables listed above including the current price of deterioration of the batteries.

The second table reports the percentage $saving_i$ with $i = [II, III]$, i.e. the ratio between the differential cost and the baseline cost

$$saving_i = \frac{cost_i - cost_I}{cost_I}$$

from which the absolute savings in terms of money can be deducted ($cost_I =$ € 166’660).

All the mentioned sums of money have been rounded up.

Table 4 Total absolute costs (with actual battery degradation cost).

		With charges	With partial charges
V1G	UVAM	/	/
	UVAR	107.290,00 €	68.850,00 €
V2G	UVAM	222.980,00 €	154.600,00 €
	UVAR	283.080,00 €	181.800,00 €

Table 5 Saving compared to the base case (with actual battery degradation cost).

		With charges	With partial charges
V1G	UVAM	/	/
	UVAR	36%	59%
V2G	UVAM	-33%	7%
	UVAR	-70%	-9%

It should be noted that the differentiation shown here between UVAM and UVAR relates to the minimum supply thresholds in terms of power quantity and duration, not considering that in the first case the total application of the charges is currently envisaged, whereas in the second case partial charges are applied, as specified in the fourth column. The economic results to be considered as realizable and updated are therefore, as far as V2G is concerned, those at the intersection between "UVAM" and "with charges" and between "UVAR" and "with partial charges". As far as the V1G is concerned, only the most profitable result should be considered, since it was observed that the car fleet, offering only takeover bids, is not able to maintain the specifications required by the UVAM.

It can be seen that, for the case analysed, the V1G is the only smart charging option that would lead to an economic advantage, corresponding to a saving of

59% compared to vehicle charging alone, in other terms equal to an annual gain of about € 97’800.

Given that the case study has to be contextualized in a future perspective, necessary to the realisation of a workplace parking with a fully electric car fleet, it was assumed a 30% reduction in the cost of batteries wear, i.e. assuming a downward trend in their price.

The values obtained in Table 5 and Table 6 are therefore obtained considering $cost_{b.w.}$=35 €/MWh (instead of 50 €/MWh).

Table 6 Total absolute costs (with discounted battery degradation cost).

		With charges	**With partial charges**
V1G	UVAM	/	/
	UVAR	95.430,00 €	57.000,00 €
V2G	UVAM	201.880,00 €	133.500,00 €
	UVAR	251.830,00 €	150.550,00 €

Table 7 Saving compared to the base case (with discounted battery degradation cost).

		With charges	**With partial charges**
V1G	UVAM	/	/
	UVAR	43%	66%
V2G	UVAM	-21%	20%
	UVAR	-51%	9%

As expected, this variation has led to a not too significant decrease in total costs. Anyway, as for batteries deterioration, in order to protect EVs owners, ARERA is required to define timing and modalities for UVAM and UVAR operators to provide vehicle owners with information on actual battery usage.

Future developments and conclusions

First of all it should be noted that the results of the optimisation model are extremely sensitive to the boundary conditions imposed by the parameters and constraints. In order to increase the accuracy of the overall performance estimates, every parameter of the problem could be considered inclusive of uncertainty, transforming the problem in examination from a deterministic case, with data input known a priori, to a stochastic problem.

Since the objective function is structured according to economic logic, the most influential parameters have proved to be the delta price between upward and downward energy on the EM and the pricing policy for the energy traded. The weight of the latter therefore depends on the energy exchanged in the subcases analysed.

Among the four theoretical alternatives implemented in the model, i.e. the V1G and V2G modes in the case of participation in UVAM or UVAR, the unidirectional mode alternative for generic mixed units was discarded because, due to the strict constraints to comply with, the algorithm isn't able to make any offer.

Overall, the application of V1G technology to a company car park has proved promising under different points of view while under current economic conditions, as expected from a quality assessment, V2G is still not profitable. In fact, the large amount of energy exchanged with the network, aggravated by the additional costs of charges and wear of batteries, makes it inconvenient. On the contrary, the economic return of the unidirectional option, even in the case of total charges, is due to the advantage in being able to charge vehicles at the price of ASM, usually much lower than that purchased in MG for the standard charging of EVs.

As for V2G, it came out that it is more inconvenient to participate in UVAR, an aggregation unit specifically designed to encourage the use of EVs; this is justified by the fact that these units were more specifically designed for the participation in the market of a few aggregated vehicles that would not be able to reach the threshold of 1 MW (instead of a large company parking, like the one considered). However, it is still possible the application of a partial charge, i.e. the charge for

UVAR, to the strategy of offering participation in UVAM obtained for this case of studies (the constraints for duration and offer threshold are widely respected).

By the way, V2G is a new and not yet mature technology. Many and different challenges, of technical, economical and even social nature, need to be overcome in order to adopt this option. Technical challenges regards EV batteries and V2G charger that are still in a growing development phase, despite the notable improvements in the past decades. As for batteries, the main issue is the gradual deterioration under charging and discharging cycles. It also increases with extreme values of battery SoC, so battery cycles should be maintained around the middle range of SoC, as in the disaggregated model of this case study where each EV SoC has to be maintained specifically in the range 40%-90%. Moreover, the complete EV charging station network with bidirectional communication infrastructure is essential for the future V2G deployment. The electrification of transport industry should likely boost developments in this research area.

Lastly, it can be underlined that V2G option, when used in combination with VRES as in the virtually aggregated units, can bring environmental benefits and numerous power quality services to the power grid. The accomplishment of the this technology needs the active participation and collaboration of government, power utilities, aggregators and EV owners.

Appropriate management system, also through the usage of optimization techniques, with incentive-based policy will be the important catalyst towards the successful V2G technology implementation.

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APPENDIX – MATLAB code

```
clear all
close all
%% Setup the Import Options
opts = spreadsheetImportOptions("NumVariables", 15);

% Specify sheet and range
opts.Sheet = "Sheet1";
opts.DataRange = "A10:O52550";

% Specify column names and types
opts.VariableNames = ["Datatimb", "Var2", "Var3", "Var4",
"Var5", "Var6", "Var7", "Var8", "Var9", "Var10", "Var11",
"OraEntra", "OraEsce", "OraEntra2", "OraEsce2"];
opts.SelectedVariableNames = ["Datatimb", "OraEntra",
"OraEsce", "OraEntra2", "OraEsce2"];
opts.VariableTypes = ["string", "string", "string",
"string", "string", "string", "string", "string", "string",
"string", "string", "double", "double", "double", "double"];
opts = setvaropts(opts, [2, 3, 4, 5, 6, 7, 8, 9, 10, 11],
"WhitespaceRule", "preserve");
opts = setvaropts(opts, [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11],
"EmptyFieldRule", "auto");

% Import the data
 tbl =
readtable('C:\Users\Iobbi\Dropbox\UVAM\V2G\timbraturedipende
nti.xls', opts, "UseExcel", false);
%tbl =
readtable("C:\Users\lpellegrino\Dropbox\UVAM\V2G\timbratured
ipendenti.xls", opts, "UseExcel", false);
%% Convert to output type
Datatimb = tbl.Datatimb;
OraEntra = tbl.OraEntra;
OraEsce = tbl.OraEsce;
OraEntra2 = tbl.OraEntra2;
OraEsce2 = tbl.OraEsce2;

%% Clear temporary variables
clear opts tbl
tic
clear all
addpath(genpath('C:\YALMIP-R20190425'));
%INPUT: previsione prezzi servizio a salire e scendere
[tempo],
%presenze [tempo x veicoli]
importdata
load('Input.mat', 'Prezzi')
Presenze_veic
%% vettore giorni feriali
date(1)=Datatimb(1);
i=2;
for j=2:length(Datatimb)
    if Datatimb(j)~=Datatimb(j-1)
```

```
        date(i)=Datatimb(j);
        i=i+1;
    end
end
%%
j=1;
for k=1:size(presenze,1)
     Prezzi_salire(k)=Prezzi(j,2);
     Prezzi_scendere(k)=Prezzi(j,3);
     if mod(k,4)==0
         j=j+1;
     end
end
Prezzi_salire=Prezzi_salire';
Prezzi_scendere=Prezzi_scendere';


tempo=(1:1:96)/96;
%%
%caso 2a/2b: cambia x_offerta (1MW - 0.2 MW), durata minima
(2h - 1h)

%%
P_salire_tot=zeros(length(tempo), length(date));
P_scendere_tot=zeros(length(tempo), length(date));
P_baseline_tot=zeros(length(tempo), length(date));
E_baseline_tot=zeros(length(tempo), length(date));
Guadagno_tot=zeros(1,length(date));


for g=1:length(date)
    if find(Datatimb==date(g))
       [P_salire(:,g), P_scendere(:,g), P_baseline(:,g),
E_baseline(:,g), Guadagno(1,g)] =
offertaDR(Datatimb,date(g));
        P_salire_tot(:,g)=P_salire(:,g);
        P_scendere_tot(:,g)=P_scendere(:,g);
        P_baseline_tot(:,g)=P_baseline(:,g);
        E_baseline_tot(:,g)=E_baseline(:,g);
        Guadagno_tot(1,g)=Guadagno(1,g);
    end
end
toc

function [P_salire, P_scendere, P_baseline, E_baseline,
Guadagno] = offerta(Datatimb, date);
Presenze_veic
tempo=(1:1:96)/96;
load('Input.mat', 'Prezzi')
addpath(genpath('C:\Program
Files\IBM\ILOG\CPLEX_Studio129\cplex\matlab\x64_win64'));
dt=0.25;
Colonnine=100;
P_colonnina=15/1000;

%Veicoli in un giorno a scelta (es: 8 Gennaio)
```

```
Veicoli= find (Datatimb==date);
presenze=(presenze(:,Veicoli));

%FUNZIONE CALCOLO CARICO
Emax=40/1000; %[MWh], Emax batteria di ogni veicolo
SoC_in=0.5;
SoC_fin=0.9;
tempo=(1:1:96)/96;
%%
[P_baseline, E_baseline]=Calcolo_Carico(Datatimb,
presenze,Veicoli, SoC_in,SoC_fin, Emax,dt);
j=1;
for k=1:size(presenze,1)
     Prezzi_salire(k)=Prezzi(j,2);
     Prezzi_scendere(k)=Prezzi(j,3);
     if mod(k,4)==0
         j=j+1;
     end
end
Prezzi_salire=Prezzi_salire';
Prezzi_scendere=Prezzi_scendere';
%%
STATO_salire=binvar(length(tempo),1);
%variabile binaria indicante la presenza di offerta a salire
STATO_scendere=binvar(length(tempo),1);
%variabile binaria indicante la presenza di offerta a
scendere

P_salire =sdpvar(length(tempo),1);
P_scendere =sdpvar(length(tempo),1);

%funzione obiettivo
Guadagno=(P_salire'*Prezzi_salire+P_scendere'*Prezzi_scender
e)*dt;

%vincoli
SoC_fin=0.9;                                            %SOC
FINALE DI OGNI BATTERIA
%vincoli tecnici batterie
P = zeros(length(tempo),1);
STATO_salire=binvar(length(tempo),1);
STATO_scendere=binvar(length(tempo),1);
E1=Emax*SoC_in*size(presenze,2);

P =  P_baseline+P_salire+P_scendere;
E = E1+cumsum(-P*dt);

%%ALTERNATIVE CARICA/SCARICA: OP1
P_colonnina=ones(1,length(P))*P_colonnina;
Veicoli_dt=(sum(presenze'))';
P_max_ch=-min(Veicoli_dt, Colonnine)*P_colonnina;
P_max_ch=P_max_ch(:,1);
P_max_dh=-P_max_ch;

%MILP
```

```
%AGGIUNGI VINCOLI E PARAMETRIZZA TEMPO

M=20;

Vincoli=[P>= P_max_ch, P<=P_max_dh];
Vincoli=[Vincoli, E<=SoC_fin*Emax*size(presenze,2), E>=E1,
P_salire>=0, P_scendere<=0];

%%
% %vincoli offerta (per almeno 2 ore)
%
% for i=max(int8(2/dt),1)+2:length(tempo)
%      Vincoli=[Vincoli,P_salire(i)>=max(P_salire(i-
max(int8(2/dt),1):i-1))-P_salire(i-max(int8(2/dt),1))];
%      Vincoli=[Vincoli,P_scendere(i)<=min(P_scendere(i-
max(int8(2/dt),1):i-1))-P_scendere(i-max(int8(2/dt),1))];
% end

% %per UVAR per almeno 1 ora
for i=max(int8(1/dt),1)+2:length(tempo)
     Vincoli=[Vincoli,P_salire(i)>=max(P_salire(i-
max(int8(1/dt),1):i-1))-P_salire(i-max(int8(1/dt),1))];
     Vincoli=[Vincoli,P_scendere(i)<=min(P_scendere(i-
max(int8(1/dt),1):i-1))-P_scendere(i-max(int8(1/dt),1))];
end

Vincoli=[Vincoli, E(end)>=E_baseline(end) ];

%aggiungo vincoli offerta UVAM
%x_offerta=1;
%per UVAR
x_offerta=0.2;
Vincoli=[Vincoli,P_salire<=M-M*STATO_salire];
Vincoli=[Vincoli,P_salire-x_offerta>=-M*STATO_salire];

Vincoli=[Vincoli,P_scendere>=M*STATO_scendere-M];
Vincoli=[Vincoli,P_scendere+x_offerta<=M*STATO_scendere];
Vincoli=[Vincoli,STATO_salire+STATO_scendere>=1];
optimize(Vincoli,-Guadagno,sdpsettings('solver','cplex'));

 P_salire=value(P_salire);
P_scendere=value(P_scendere);

%
tempo=(1:1:96)/96;           %deve essere un array da 0 a 1
plot(tempo,P_baseline)
datetick('x', 'HH:MM')
xlabel('t [h]')
ylabel('P [MW]')
hold on
plot(tempo,P_salire)
hold on
plot(tempo,P_scendere);
Powers={'baseline','upward Power','downward Power'};
legend(Powers)
datetick('x', 'HH:MM')
```

```
xlabel('t [h]')
ylabel('P [MW]')

E_OPT=value(E);
POT=value(P);
Guadagno=value(Guadagno);
clear i j dt

function [P_baseline E_baseline]= Calcolo_Carico(Datatimb,
presenze,Veicoli, SoC_in,SoC_fin, Emax,dt)
Emax=40/1000; %[MWh], Emax batteria di ogni veicolo

E_dacaricare=Emax*(SoC_fin-SoC_in);
tempo_pr=sum(presenze)/4;

for i=1:length(tempo_pr)
    if tempo_pr(i)==0
        P_load(1,i)=0;
    else
        P_load(1,i)=E_dacaricare/tempo_pr(i);
    end
end

P_baseline=-P_load.*presenze;

P_baseline=sum(P_baseline,2);

%calcolo E_baseline
E_baseline=cumsum(-
P_baseline*dt)+(SoC_in*Emax)*length(Veicoli);
clear i

end
%%
%COSTI giornalieri NO MB, UVAM , UVAR
dt=0.25;
c_baseline=77; % €/MWh  PUN medio 2018 fascia F1, prezzi
aziendali
costo_us_batt= 50; %€/MWh costo uso batteria
oneri_sis=50.85;     %€/MWh  caso aziendale
oneri_rete=8.46;
oneri_disp=11.55;
oneri_altro=4.021;
c_oneri_tot=oneri_sis+oneri_rete+oneri_disp+oneri_altro;



IVA=0.22;
accise=12.5;   %€/MWh

%OPZIONE 1: solo baseline
E_baseline_delta=E_baseline(end,:)-E_baseline(1,:); %E
caricata /gg
C1=E_baseline_delta*(c_baseline+c_oneri_tot+accise);
C1=C1*(1+IVA);
```

```
%OPZIONE 2a: con oneri salire/scendere, usura batterie
for i=1:length(date)
    for j=1:length(tempo)
        if P_salire(j,i)>-
(P_baseline(j,i)+P_scendere(j,i))+0.01
            C2a_day(j,i)=-
((P_salire(j,i)*dt)'*(Prezzi_salire(j)))'+P_baseline(j,i)*dt
*(c_baseline+c_oneri_tot+accise)*(1+IVA);  %solo guadagno e
no oneri quando funzionamento da gen e no base
        else
            C2a_day(j,i)=((-
P_scendere(j,i)*dt)'*(Prezzi_scendere(j)+c_oneri_tot+accise+
costo_us_batt))'*(1+IVA)-
((P_salire(j,i)*dt)'*Prezzi_salire(j))'-
((P_salire(j,i)*dt)'*(c_baseline+c_oneri_tot+accise)*(1+IVA)
)';
        end
    end
end
% for  i=1:length(date)
%     C2a_day(j,i)=((-
P_scendere(j,i)*dt)'*(Prezzi_scendere(j)+c_oneri_tot+accise+
costo_us_batt))'*(1+IVA)-
((P_salire(j,i)*dt)'*Prezzi_salire(j))'-
((P_salire(j,i)*dt)'*(c_oneri_tot+accise)*(1+IVA))'
% end
C2A=C1+sum(C2a_day,1);
%OPZIONE 2b: senza parte degli oneri scendere, usura
batterie
c_oneri=oneri_sis+oneri_rete;
%E_scendere_tot=cumsum(P_scendere_tot*dt); %neg
C2B=C2A+(sum(P_scendere,1)*dt*c_oneri);

C1y=sum(C1); %baseline annuale
C2Ay=sum(C2A); %UVAM annuale
C2By=sum(C2B); %UVAR annuale

risp2A=(C1y-C2Ay)/C1y;
risp2B=(C1y-C2By)/C1y;
money2a=C1y*risp2A;
money2b=C1y*risp2B;
%%
%numero offerte
P_salireh=reshape(P_salire, 1, 96*267);

for i=1:length(P_salireh)
    if P_salireh(i)< 0.2
        P_salireh(i)=NaN;
    end
end
P_scendereh=reshape(-P_scendere, 1, 96*267);
for i=1:length(P_scendereh)
    if P_scendereh(i)<0.2
        P_scendereh(i)=NaN;
    end
end
```