POLITECNICO
MILANO 1863

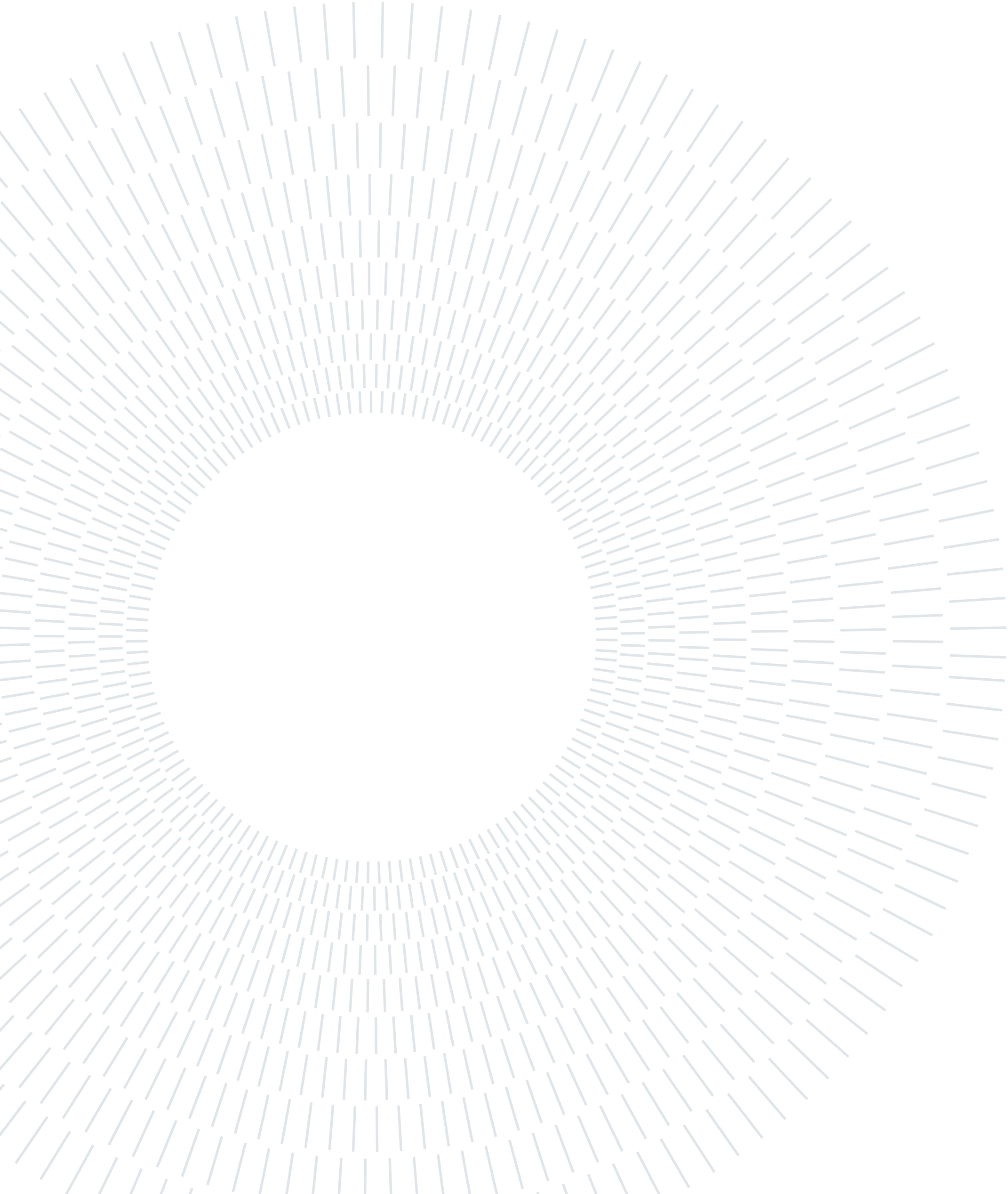
SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Mobility patterns as a basis for integrating electric vehicles in ancillary services market

Tesi di Laurea Magistrale in
Energy Engineering - Ingegneria Energetica

Author: **Luca Giovanni Brigatti**

Student ID: 10609904
Advisor: Prof. Marco Merlo
Co-advisors: Matteo Spiller, Corrado Maria Caminiti
Academic Year: 2022-23



Abstract

This research explores the capability of a fleet of electric vehicles (EVs) to contribute to ancillary services for the power grid, considering the rising presence of EVs in the car market and the growing need for such services as a result of the expansion of variable renewable energy sources. The methodology developed is versatile and suitable for a variety of contexts. The focus is on e-mobility within Lombardy region, starting with an analysis of the impact of EV charging on the power grid, and then assessing the contribution that a grouped set of EVs can make to grid stability and the associated economic returns. The proposed approach is a bottom-up model that analyzes individual trips taking place in a typical day within Lombardy. This detailed approach is pivotal for understanding the collective behavior of the entire EV fleet. A thorough, realistic analysis requires the model to be grounded in real-world data, specifically from a mobility survey by Lombardy region, presented as an Origin-Destination (OD) matrix. Using this data, a traffic model calculates travel times while considering the actual traffic conditions. Charging stations are modeled to reflect the real-world scenario of charging power and availability. By analyzing this information and conducting an energy assessment, it's possible to ascertain the required energy amount and the necessary recharge time. Estimating the duration of stay at the destination based on the trip's purpose allows for the determination of the time frame within which charging needs to occur. Aggregating individual journey data enables the deduction of the EV pool's collective behavior. The potential contribution of this aggregate to the grid, as requested by the Transmission System Operator (TSO), is then calculated, considering both the needs of the grid and the users. The model applies load shifting logic to evaluate primary frequency regulation and tertiary reserve. It offers insights about advantages and disadvantages of various configurations in relation to aggregate control logic. In the most effective configuration modelled, in an EV penetration scenario of 2.5%, equivalent to about 75'000 vehicles, the primary frequency regulation band overcomes a minimum daily value of 4 MW, generating overall yearly revenues from services provision of about €800'000. The primary limitation of the proposed methodology is the difficulty in simulating the daily behavior of individual vehicles, including their state of charge and potential charging locations. The available data set did not allow for tracking the movements of each car throughout the day, limiting the ability to reach a further level of detail in the analysis of each vehicle's potential contribution to grid services. The outcomes of the simulations show a notable potential to contribute to grid stability. While the financial benefits derived from offering the examined services are modest, the influence on charging processes is also minimal.

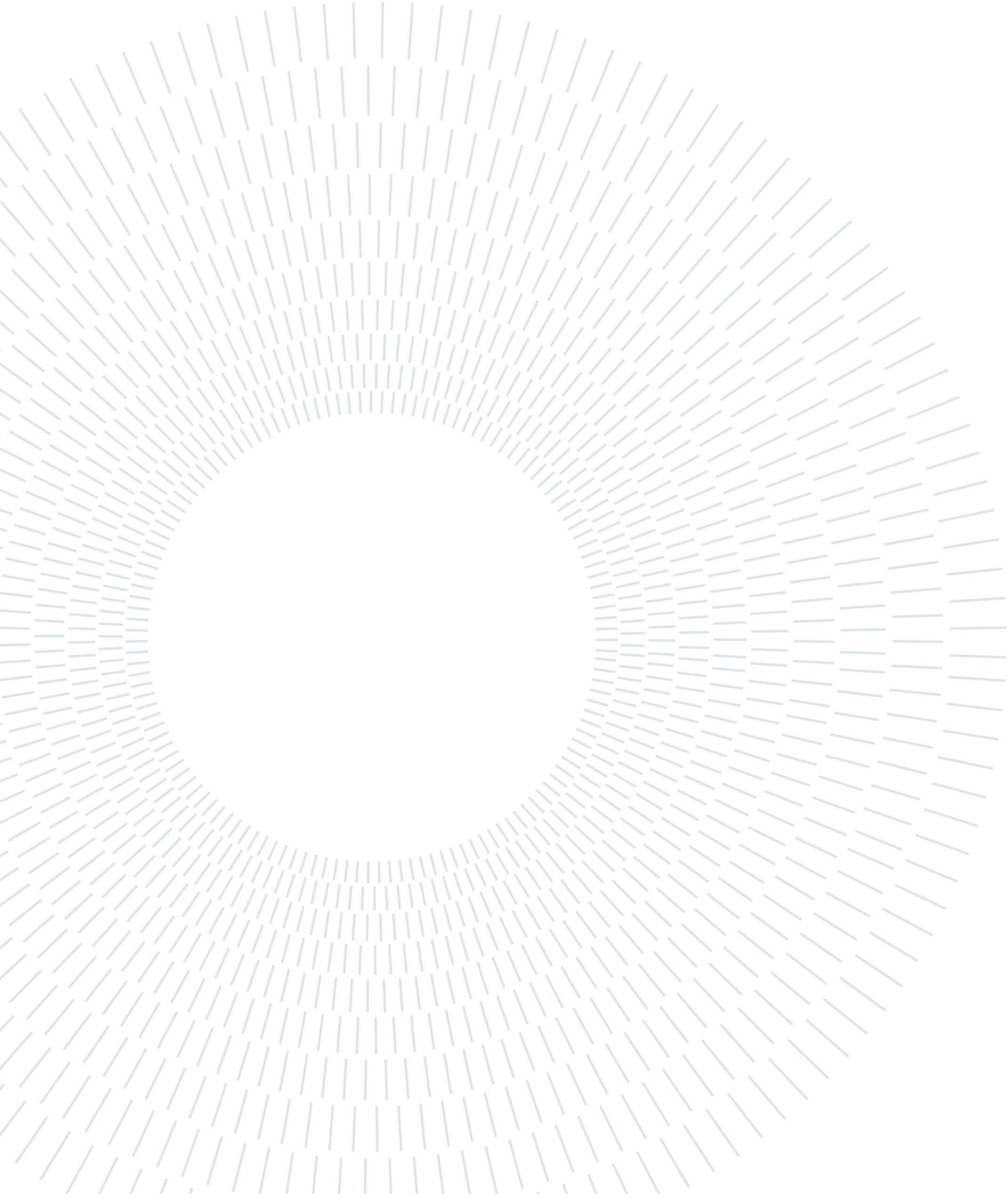
Keywords: EVs, ancillary services, routing, OD, smart charging

Abstract in lingua italiana

Questo studio indaga il potenziale di un aggregato di veicoli elettrici nel partecipare ai sevizi ancillari per la rete elettrica, alla luce della loro crescente presenza nel mercato automobilistico e della crescente domanda di questo tipo di servizi dovuta all'espansione di fonti di energia rinnovabile non pianificabili. La metodologia sviluppata mira ad essere adattabile e applicabile a diversi contesti e aree geografiche. L'attenzione è focalizzata sulla mobilità elettrica all'interno della Lombardia, iniziando con un'analisi dell'impatto della ricarica dei veicoli sulla rete elettrica, e poi valutando il contributo che un aggregato di auto elettriche può fornire alla stabilità della rete e i relativi ritorni economici. Il metodo scelto è un modello bottom-up che analizza i singoli viaggi effettuati all'interno di regione Lombardia. Questo approccio dettagliato è fondamentale per comprendere il comportamento collettivo dell'intera flotta di veicoli. Un'analisi approfondita e realistica richiede che il modello sia basato su dati affidabili, che nel caso in esame sono tratti da un'indagine sulla mobilità condotta da Regione Lombardia, presentata come una matrice Origine-Destinazione (OD). Utilizzando questi dati, il modello di traffico calcola i tempi di viaggio considerando le effettive condizioni della rete stradale. Le stazioni di ricarica sono modellate per riflettere lo scenario reale di potenza e disponibilità di ricarica. Analizzando queste informazioni e conducendo una valutazione energetica, è possibile determinare la quantità di energia richiesta ed il tempo necessario per la ricarica. Stimando la durata della permanenza a destinazione in base allo scopo del viaggio, è quindi possibile determinare l'intervallo di tempo entro il quale deve avvenire la ricarica. Aggregando i dati dei singoli viaggi, si può dedurre il comportamento collettivo della flotta di auto elettriche. Il potenziale contributo di questo aggregato alla rete viene poi calcolato, considerando sia le richieste dell'operatore del sistema di trasmissione, sia le esigenze di ricarica dei singoli automobilisti. Il modello applica una logica di spostamento del carico per valutare la regolazione della frequenza primaria e la riserva terziaria. Lo studio offre spunti su vantaggi e svantaggi delle varie configurazioni in relazione alla logica di controllo dell'aggregato. Nella configurazione più efficace simulata, in uno scenario di penetrazione delle auto elettriche pari al 2,5%, equivalente a circa 75'000 veicoli, la banda di regolazione della frequenza primaria attesta il minimo giornaliero oltre i 4 MW, generando ricavi complessivi dalla fornitura dei servizi per circa €800’000 all’anno. La principale limitazione della metodologia proposta è la difficoltà nel simulare il comportamento quotidiano dei singoli veicoli, incluso il loro stato di carica e le potenziali località di ricarica. Il set di dati disponibile non permette di tracciare i movimenti di ogni auto durante l’intera giornata, limitando la capacità di raggiungere un ulteriore livello di dettaglio nell’analisi del potenziale contributo di ogni veicolo ai servizi di rete. I risultati delle simulazioni mostrano un notevole potenziale per contribuire ai prodotti previsti dal mercato elettrico per il controllo della stabilità della rete. Sebbene i benefici economici derivanti dall’offerta dei servizi esaminati siano modesti, l’influenza sui processi di ricarica è a sua volta molto contenuta.

Parole chiave: veicoli elettrici, servizi ancillari, origine destinazione, routing, ricarica intelligente

Contents



1 | Introduction

1.1. Mobility context in Europe

Mobility sector is facing a dramatic change and its future is uncertain more than ever. In Figure 1.1 data on CO_2 emissions from different sectors in EU are reported. It is possible to notice that transport sector in 2019 accounted for 1123 Mt of CO_2 representing almost the 30% of the total CO_2 emitted by European countries. The imperative need to reduce the environmental impact of transportation is pushing this transition. Europe is willing to take a leading position on this regard, in fact, the European Green Deal aims to achieve a 90% reduction in transport-related greenhouse gas emissions by 2050 [1].

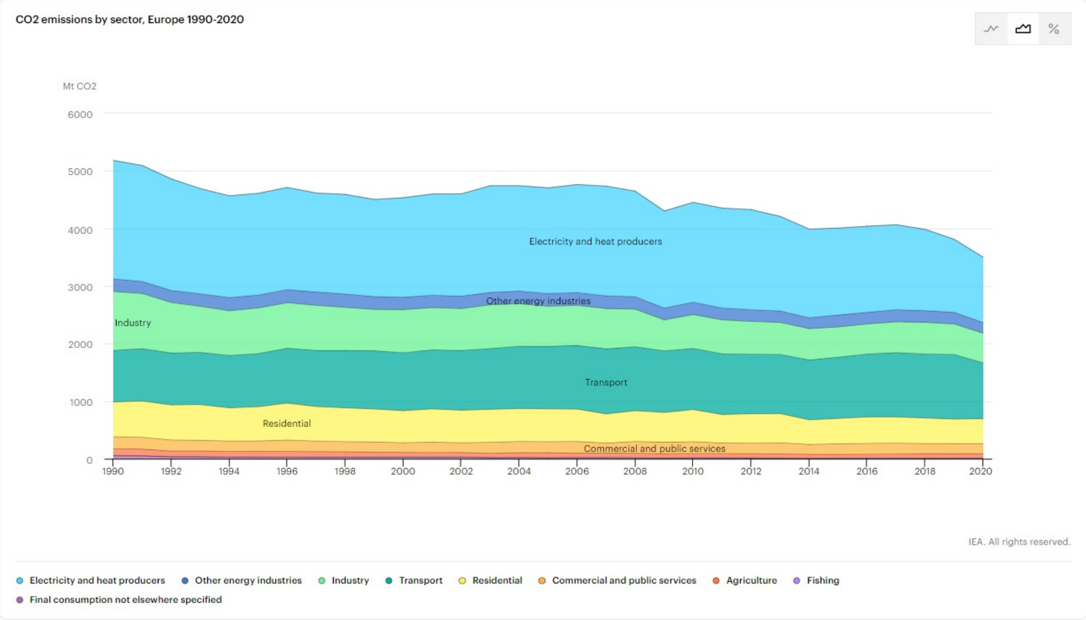


Figure 1.1: CO_2 emissions per sector EU [1]

To have a deeper understanding regarding greenhouse gases emissions related to transport sector, a further breakdown of how these emissions are allocated among different typologies of transportation is reported in Figure 1.2. Road transport is clearly the most relevant area so a further detail on the CO_2 emissions from different typologies of vehicles is provided in the following. Passenger cars are by far the most impacting, accounting for almost the 45% of total CO_2 emissions attributable to transport sector.

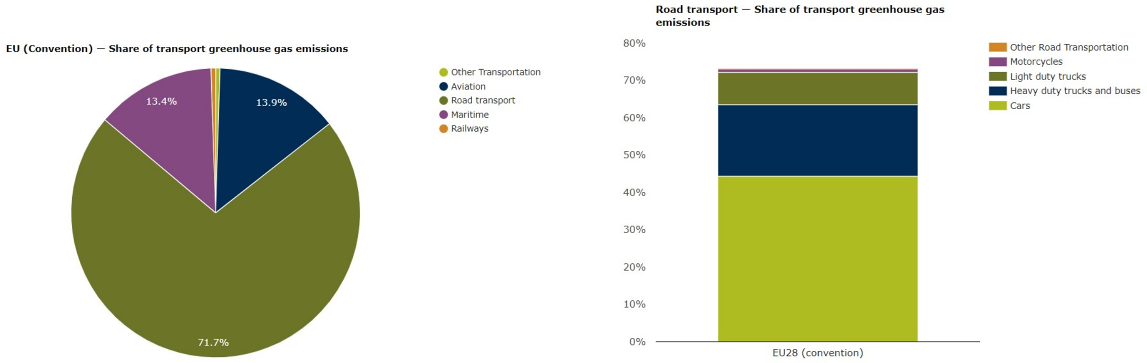


Figure 1.2: Breakdown of CO_2 emissions for EU28 (2017 data) [2]

1.2. Outlook on EVs

In order to substantially reduce CO_2 emissions from passenger cars different technologies are currently available. Automotive sector is particularly competitive and several factors simultaneously contribute to whether a technology is deployed or not. Currently what appears to be the preferred short to mid term solution chosen by all the most important carmakers is electrification through BEV.

To understand this trend it is essential to be familiar with the typologies of electrified vehicles that are currently available on the market: [3] [4]

- Mild Hybrid Electric Vehicles (MHEVs): like the name implies, a mild hybrid system is not going to propel the vehicle on electric power alone. The system is used to give a small boost to the vehicle's gasoline engine, typically upon acceleration from a dead stop, and to assist in removing the burden of power-hungry systems, such as air conditioning, on the gasoline engine. Normally found in the form of 48 volt electric systems, mild hybrids do not need to be plugged in. Instead, the batteries are recharged through a combination of power from the gasoline engine, and energy recovered when the vehicle brakes (also known as regenerative braking).
- Full Hybrid Electric Vehicles (FHEV): they have both an internal combustion engine and an electric motor to drive the car. The energy for the battery is gained through regenerative braking, which recoups otherwise lost energy in braking to assist the gasoline engine during acceleration. In a traditional internal combustion engine vehicle, this braking energy is normally lost as heat in the brake pads and rotors.

- Plug-in Hybrid Electric Vehicles (PHEVs): they have both an engine and electric motor to drive the car. Like regular hybrids, they can recharge their battery through regenerative braking. They differ from regular hybrids by having a much larger battery, and being able to plug into the grid to recharge. While regular hybrids can (at low speed) travel only few kilometers before the gasoline engine turns on, PHEVs can travel for tenths of kilometers before their internal combustion engines provide assistance. Once the all-electric range is depleted, PHEVs act as regular hybrids, and can travel several hundred miles on a tank of gasoline.
- Electric Vehicles with Range Extender (EREVs): they utilize their gasoline engine to charge the battery or power the electric motor when the battery is empty. Depending on the size of the gasoline engine, the extra kilometers that can be covered range from few tenths to hundreds. Among the mentioned technologies this one is currently the least adopted one.
- Battery Electric Vehicles (BEVs): they are fully electric vehicles with rechargeable batteries and no gasoline engine. All energy to run the vehicle comes from the battery pack which is recharged from the grid.

Figure 1.3 presents a schematic description of the main differences among the most commonly adopted typologies of powertrains for electrified vehicles currently available on the market.

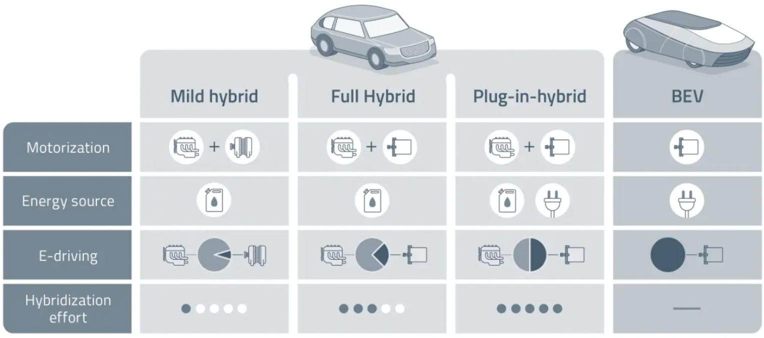


Figure 1.3: Most common powertrain designs for electrified vehicles on the market [5]

The shift from internal combustion engine cars to fully electric vehicles is a rough path since it includes a sensible impact on final users' habits regarding the issues related to range anxiety and duration of charging processes. The current situation is depicted in Figure 1.4 where shares of new passenger cars by fuel type are reported. It is clear how traditional powered cars still cover a large share of the market but simultaneously hybrid and fully electric vehicles are reaching a great importance. It is crucial to acknowledge that vehicles that can be connected to the grid (PHEVs and BEVs) add up to more than 20% of total sales. [5]

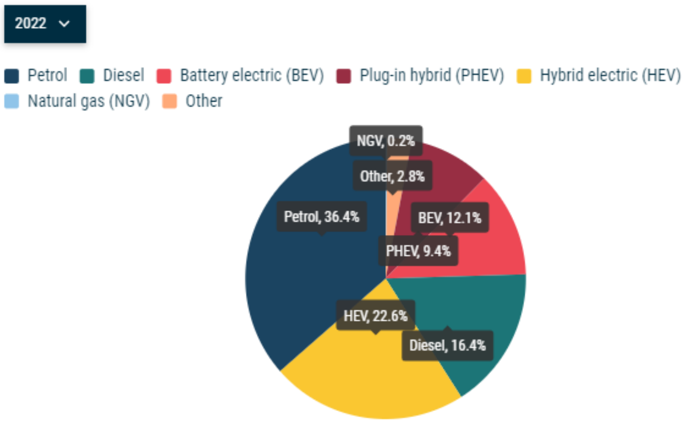


Figure 1.4: Share of new cars sold in EU by fuel type [5]

Having a closer look to PHEVs and EVs, in Figure 1.5 the trend of shares of new registration of EVs is reported. It should be highlighted that the trend is continuously increasing with a particular steep slope in the last couple years, indicating an increase in competitiveness of these technologies and in the interest in final users.

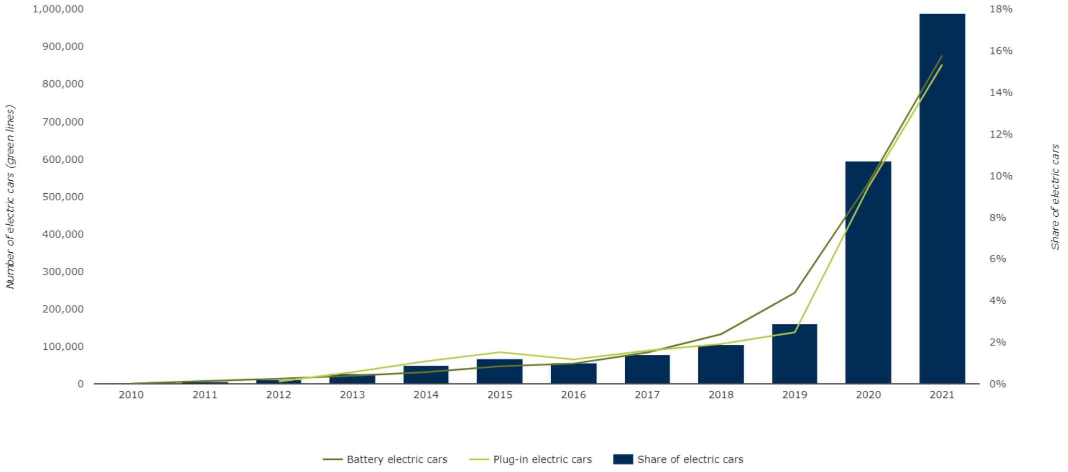


Figure 1.5: Share of EVs sold in EU [6]

To critically analyse the previously shown trends, it is crucial to highlight that in the years from 2020 on, mainly due to the COVID 19 pandemic and to the resulting economic situation, the overall sales in the automotive sector show a relevant drop. In particular the most impacted segments by this fall are the ones belonging to the lower side of the market, where BEV and PHEV, due to their higher cost, are less present. Figure 1.6 Figure 1.7

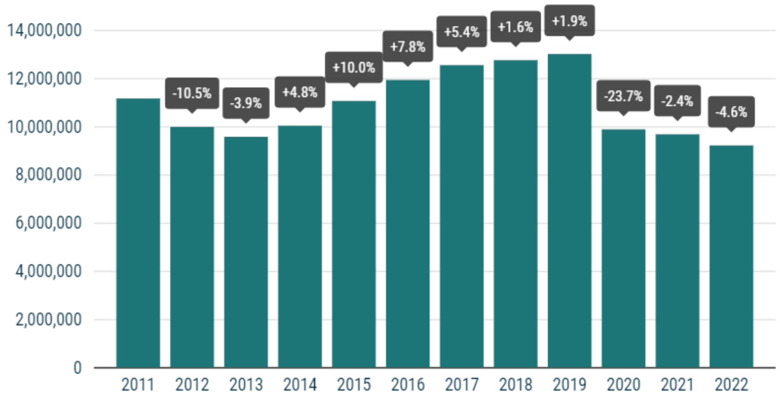


Figure 1.6: Number of new cars sold in EU [7]

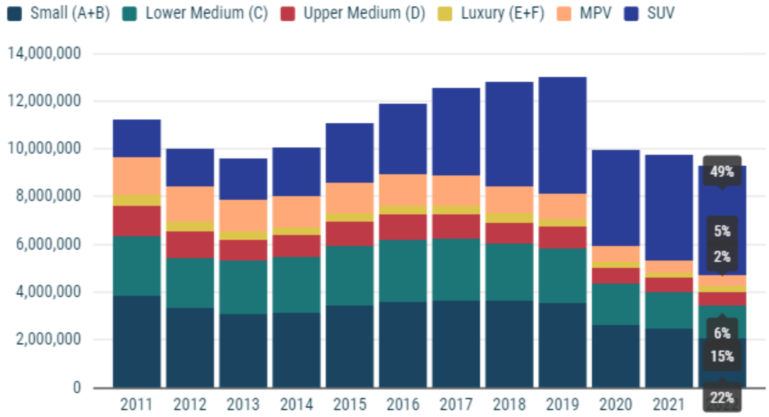
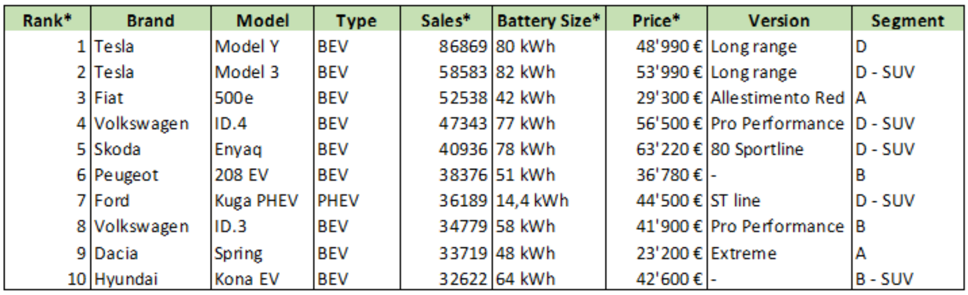


Figure 1.7: Number of new cars sold in EU by segment [7]

To further detail the EVs that are being purchased by European customers in Figure 1.8 [1] the top ten of the best selling EVs in Europe in 2022 is reported [8]. Only one PHEV is present in the the list (the Ford Kuga PHEV) while all the other vehicles are BEV. The Kuga PHEV's battery size is representative for its typology of vehicle. Concerning the BEVs present in the table the average capacity settles at 64 kWh.



Rank*	Brand	Model	Type	Sales*	Battery Size*	Price*	Version	Segment
1	Tesla	Model Y	BEV	86869	80 kWh	48'990 €	Long range	D
2	Tesla	Model 3	BEV	58583	82 kWh	53'990 €	Long range	D - SUV
3	Fiat	500e	BEV	52538	42 kWh	29'300 €	Allestimento Red	A
4	Volkswagen	ID.4	BEV	47343	77 kWh	56'500 €	Pro Performance	D - SUV
5	Skoda	Enyaq	BEV	40936	78 kWh	63'220 €	80 Sportline	D - SUV
6	Peugeot	208 EV	BEV	38376	51 kWh	36'780 €	-	B
7	Ford	Kuga PHEV	PHEV	36189	14,4 kWh	44'500 €	ST line	D - SUV
8	Volkswagen	ID.3	BEV	34779	58 kWh	41'900 €	Pro Performance	B
9	Dacia	Spring	BEV	33719	48 kWh	23'200 €	Extreme	A
10	Hyundai	Kona EV	BEV	32622	64 kWh	42'600 €	-	B - SUV

Figure 1.8: Best selling EVs in EU [8]

---

[1] The rank and number of sales refer to the period from January to October 2022. Battery Size and Price refers to the Version reported in the table and are took from Italian catalog

1.3. Concerns and opportunities

Trends on the adoption of EVs depict a radical transformation in a sector of paramount importance like the transportation one. This clearly leads to both concerns and opportunities, the main ones are depicted in Figure 1.9.

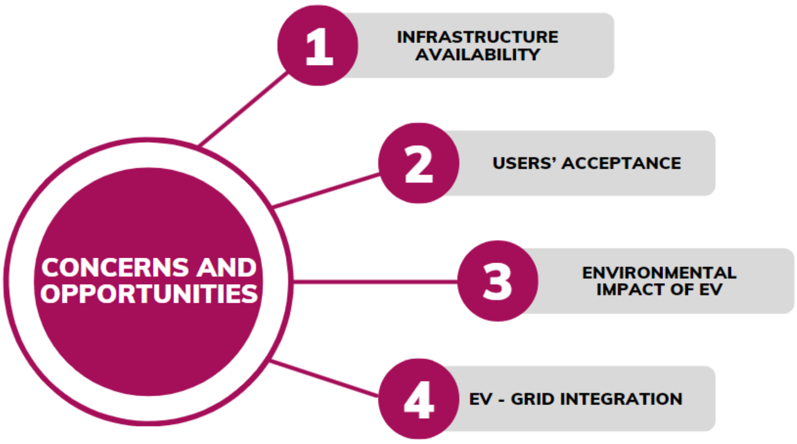


Figure 1.9: Main concerns and opportunities related to EV adoption

To enable EVs to be a viable alternative to traditional combustion engine cars, it is essential that the deployment of charging stations goes hand in hand with the adoption of EVs, to allow users to charge whenever and wherever needed. Users' acceptance is an issue that is strongly linked to the first concern, since charging times and accessibility of charging stations, together with mileage of the car, are the main worries for users. The environmental impact of an EV is a truly wicked problem since the real overall impact depends both on how the core components are manufactured and from how the electric energy used to charge the batteries is produced. In the following section, a Life Cycle Assessment (LCA) conducted by the European Environmental Agency is reported to better clarify this topic. Finally the integration between EVs and grid is the core of this work and could be in the close future either a delicate issue or an interesting opportunity. EVs interact with the power system whenever they are connected to a charging point. EVs charging can cause operational challenges and require upgrades based on the power asked to the system and the specific location from which the power is drawn. The impacts can be classified as those affecting the capacity limits of the different components of the network, those regarding the power quality for the end users and those involving larger power system: [9]

- Line, transformer, and feeder loading: sustained loading beyond the physical capacity of the components of the grid can lead to premature ageing or permanent damage. Operating limits on current, voltage drops, frequency deviation, temperature and losses are placed in order to reduce the likelihood of this problem. Components must be upgraded or reinforced if loading is expected to regularly exceed these limits.

- Power quality: the current drawn for EV charging may lead to imbalances in the network voltage if EV charging is done on a single phase and may also lead to harmonic distortions. Lower power quality could lead to the eventual damage of other nearby electrical appliances, and hence distribution utilities are subject to power quality indicators, such as contractual voltage limits and harmonic distortion limits.
- Systemwide impacts: charging during peak periods can exaggerate the peak demand and the subsequent need for peak generation capacity. The extent to which these grid impacts manifest depends on the charging use cases that develop and where they occur, which in turn are based on the electrification of vehicles. Defining an electric mobility strategy is the first step in assessing the grid impacts resulting from transport electrification.

In order to tackle the presented issues, create value for EV users and save money on infrastructure upgrades, a strategy to coordinate and control charging processes of EVs could represent an interesting solution. The term Smart Charging or V1G refers in fact to the capability of an EV to be controlled during the charging process in order to modulate its charging power to better fit grid needs. On the other hand V2G *"Vehicle to Grid"* refers to a more advanced technology that allows the EV to actively exchange power with the grid in a bidirectional charging process: if the grid needs an additional injection of power, connected EVs with this technology can partially discharge their battery packs to contribute to the grid energy needs. Research and implementation of these technologies could not only alleviate the problems of the additional load related to charging processes but also exploit the potential of EVs as a precious asset for grid stability. [10]

1.4. Life cycle assessment of an EV

The life cycle assessment of EVs is an hot topic discussed in depth in many works in literature. Since it is not the focus of this work, this section provides only a brief overview on the thematic, taking as a reference the extensive report written by the European Energy Agency [11]. The evaluation of the overall environmental impact of an electric vehicle is an extremely challenging task since requires to take into account several aspects: from the manufacturing through the use of the car to the end of life. In Figure 1.10 the steps to be analysed are reported.

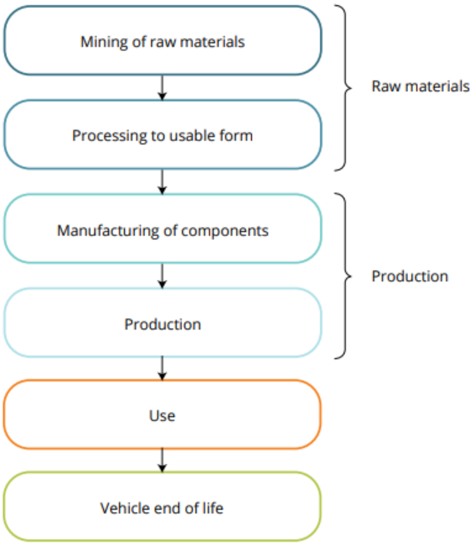


Figure 1.10: Crucial steps in the LCA of an EV

For what concerns the raw materials extraction stage, the impact in terms of toxicity and greenhouse gases emission is greater with respect to traditional internal combustion engine vehicles (ICEVs) and most of this difference is related to rare materials implied in the production of batteries and copper needed in power electronics. In Figure 1.11 is reported a schematic representation of the critical materials needed in the production of an EV.

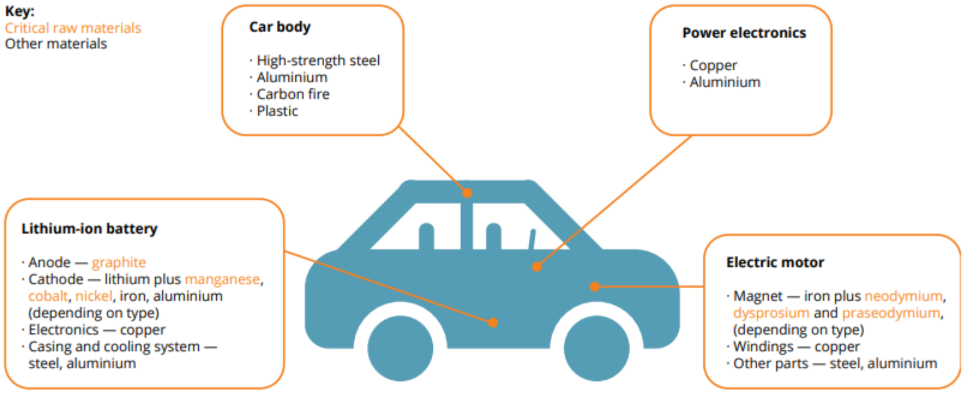


Figure 1.11: Key materials for EVs production

As for the raw materials extraction stage, also in the production stage the environmental impact of an electric vehicle is significantly bigger than the one concerning an ICEV. In Figure 1.12 is shown a comparison between the two vehicle typologies with respect to the impact of the production in six different areas. It is clear how, once again, the battery is the most critical component.

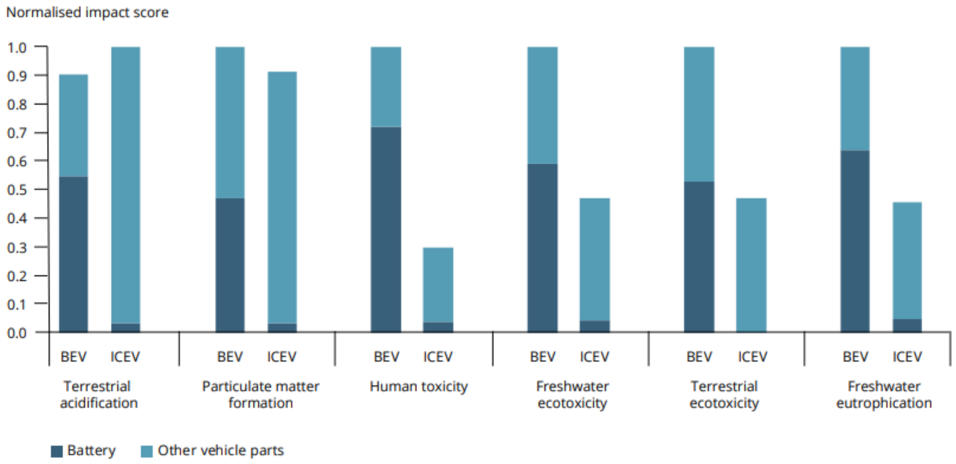


Figure 1.12: Impact comparison of production stage

The footprint evaluation for the use phase of a vehicle needs to account for the impact related to the whole processing of energy: from extraction to final conversion for mobility use. This overall energy usage is referred to as *"well to wheel"* and results from the sum of two distinct stages named *"well to tank stage"*, namely all the treatments needed to produce and deliver energy to the vehicle and *"tank to wheel stage"*, that refers to the energy conversion processes happening in the vehicle to allow motion. In Figure 1.13 a representation of the main processes for the wheel to wheel impact evaluation of EVs and ICEVs.

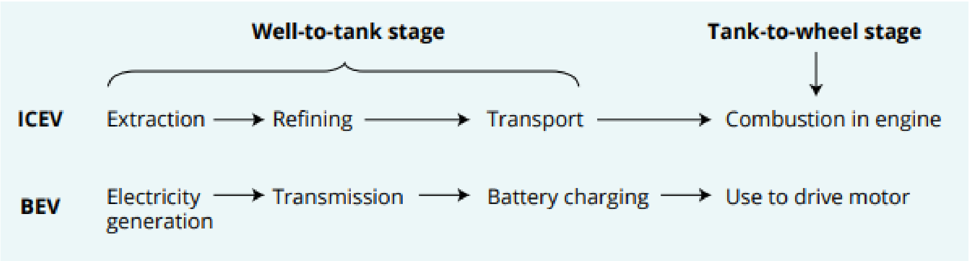


Figure 1.13: Definition of use stage impacting processes

Concerning the use stage, for BEVs the greenhouse gases emissions generated are attributable to the wheel to tank stage. Keeping into account the high efficiency of transmission and battery charging processes, the core element to analyse is electricity generation. The energy mix that is employed for charging the car is of paramount relevance while assessing the impact in question. In Figure 1.14 it can be observed how different the amount of GHG emissions per MWh of energy produced can be dependent on the energy source used. From 2017 data on the study took as a reference [11], the estimated use stage GHG emissions of a typical BEV ranged from 9 gCO2/km in Sweden, where nuclear and hydro-electric generation dominate, to 234 gCO2/km in Latvia, which mainly imports electricity from coal from neighbouring countries. Keeping into account that the average emission level of an ICEV is around 140 gCO2/km it is evident how the energy mix of a country is essential to have a real reduction in greenhouse gases emissions with the deployment of EVs.

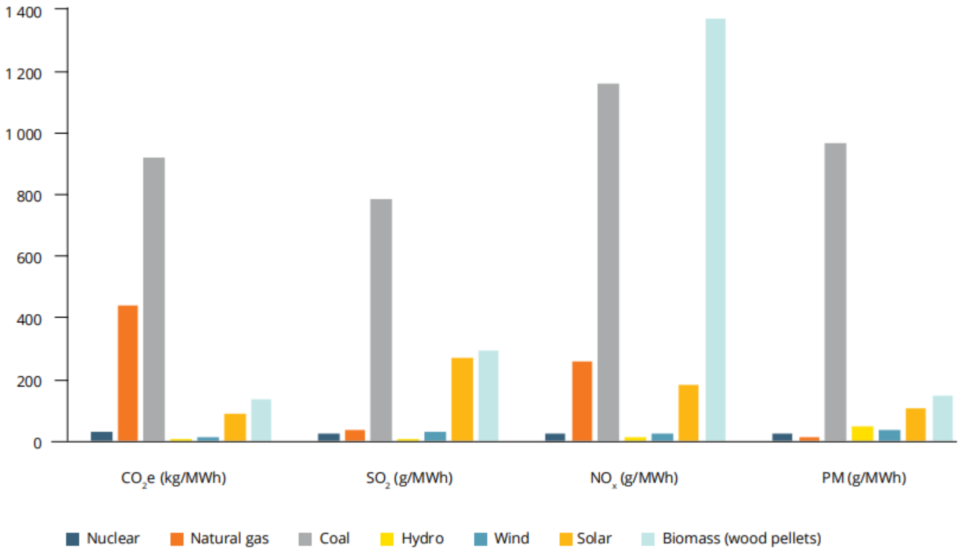


Figure 1.14: Overall GHG emissions per MWh for different energy sources

Concerning the end of life stage of an EV there are several options currently under research mainly related to extend lifetime of batteries using them in a context that requires lower performance or to recycle precious materials. Figure 1.15 shows a schematic representation of the most relevant possibilities for managing this stage.

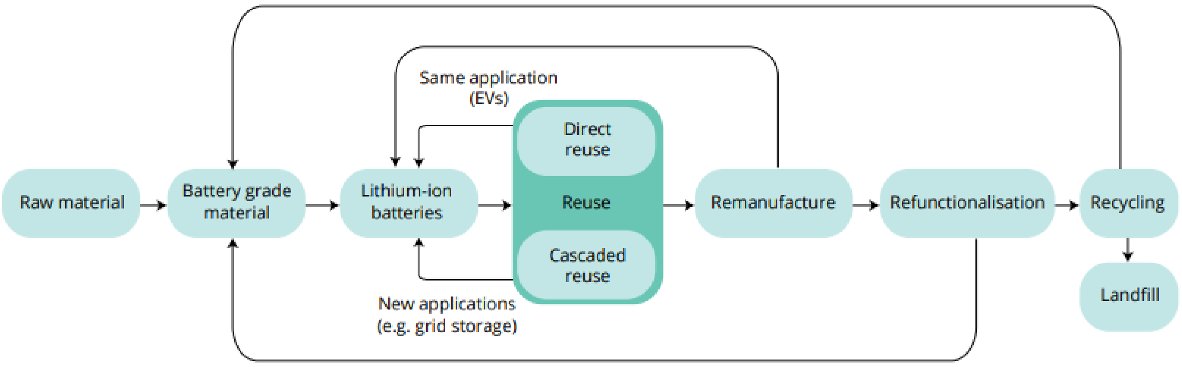


Figure 1.15: Possible options for end of life management of EV batteries

To sum up in, Figure 1.16 is depicted the impact of different typologies of vehicles according to GHG emissions and it is once again clear how crucial the energy mix is essential for the overall emissions computation for BEVs. There is also a lot to be done to reduce the impact of extraction of rare earths and production of batteries, possibly also implementing effectively some of the end of life options proposed.

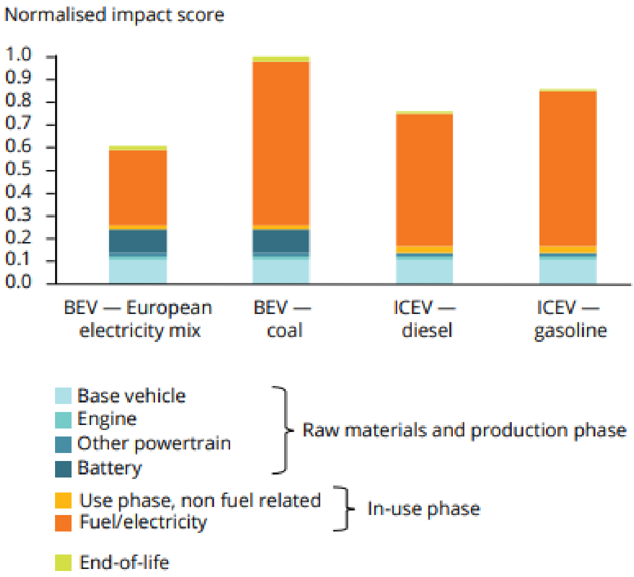
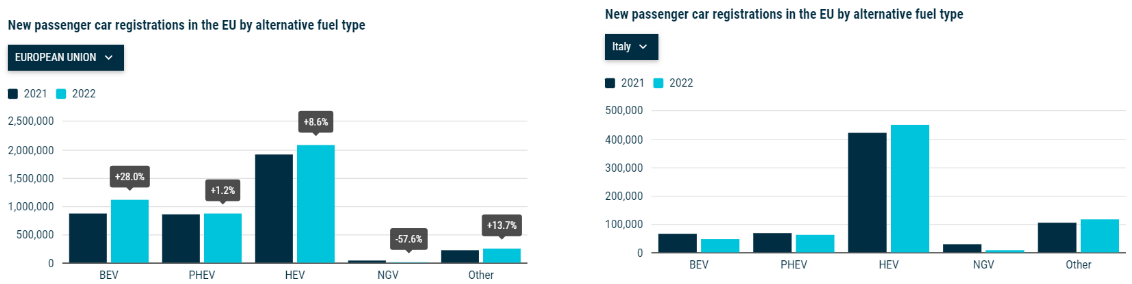


Figure 1.16: Comparison of overall GHG emissions for different typologies of vehicle

1.5. E-Mobility in Italy

Since this research is focused on mobility in Lombardy region it is essential to provide some additional details on e-mobility diffusion in Italy. As it can be noticed in Figure 1.17, in Italy the diffusion of EVs is slower than the European average.



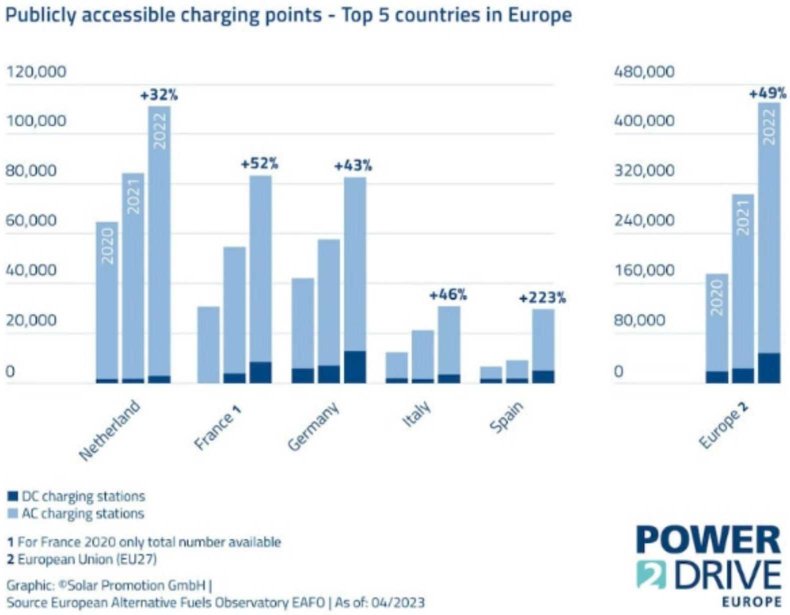
(a) New cars sold in EU by fuel type [5]

(b) New cars sold in Italy by fuel type [5]

Figure 1.17: Comparison between new cars sold in EU and Italy by fuel type [5]

The reasons of this trend are complex and surely influenced by a number of different reasons. Among them, high cost of EVs with respect to a traditional car of the same segment and to the adversity of leaving the convenience of the almost instantaneous refueling of internal combustion engines for the much longer times required by BEVs to recharge are surely of high relevance.

Charging infrastructure plays a crucial role for final users acceptance. In Figure 1.18 the number of public accessible charging points in different European countries is reported. Italy is far behind France and Germany, but the deployment of new charging points grows consistently.


Publicly accessible charging points - Top 5 countries in Europe

1 For France 2020 only total number available
2 European Union (EU27)

Graphic: ©Solar Promotion GmbH |
Source European Alternative Fuels Observatory EAFO | As of: 04/2023

Figure 1.18: Number of publicly available charging points [12]

1.6. Smart charging context

Smart charging or intelligent charging refers to a system where the EV and the charging station can be dynamically controlled by the charging operator thanks to a data connection. As opposed to traditional charging devices that are not connected to the cloud, smart charging allows the charging station owner to monitor, manage, and restrict the use of their devices remotely to optimize energy consumption. [13]

In a future scenario where electric vehicles will constitute the vast majority of the circulating fleet, technologies that enable the control of electricity demand will be fundamental to smooth the additional strain that will be required to the distribution grid.

The disruptive rise in non predictable renewable energy power plants connected to the grid will require the deployment of storage technologies and heavy investments in the distribution infrastructure. Smart charging and V2G could enable the decentralised storage capacity embedded in batteries of EVs to play an important role in this scenario, seen their flexible and adaptable energy demand.

In the following, an overview of the current situation and trends regarding the major non predictable renewable energy sources in Europe is provided. Figure 1.19 shows the output of the *WindEurope* scenario regarding wind energy penetration by 2030. It is clear how both in terms of installed capacity and share of demand covered, wind energy will be a key player in electricity markets.

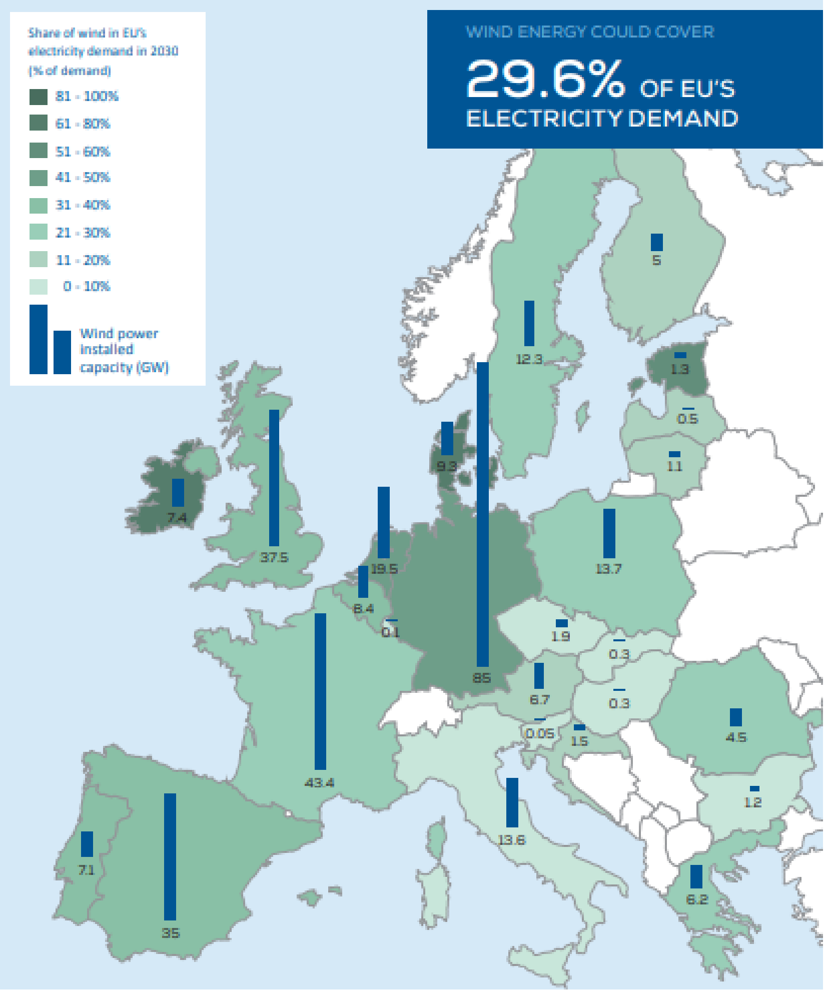


Figure 1.19: Scenario on wind energy penetration in EU by 2030 [14]

The other most relevant actor as regards non predictable energy sources is Photovoltaic (PV). From *McKinsey* report's outlook [15] shown in Figure 1.20, Europe is planning a major ramp-up of PV-based electricity to address its energy challenges, which include meeting its climate ambitions, managing a large part of its electrification, decarbonising the electricity grid, and becoming less reliant on other countries. As part of its "EU solar energy strategy" [16] the region has announced a 750 GW target of installed solar-

PV capacity by 2030 up from 224 GW of installed capacity in 2022. This represents a considerable step up in annual installations, going from 26 GW in 2021 to around 70 GW per year in the second half of this decade.

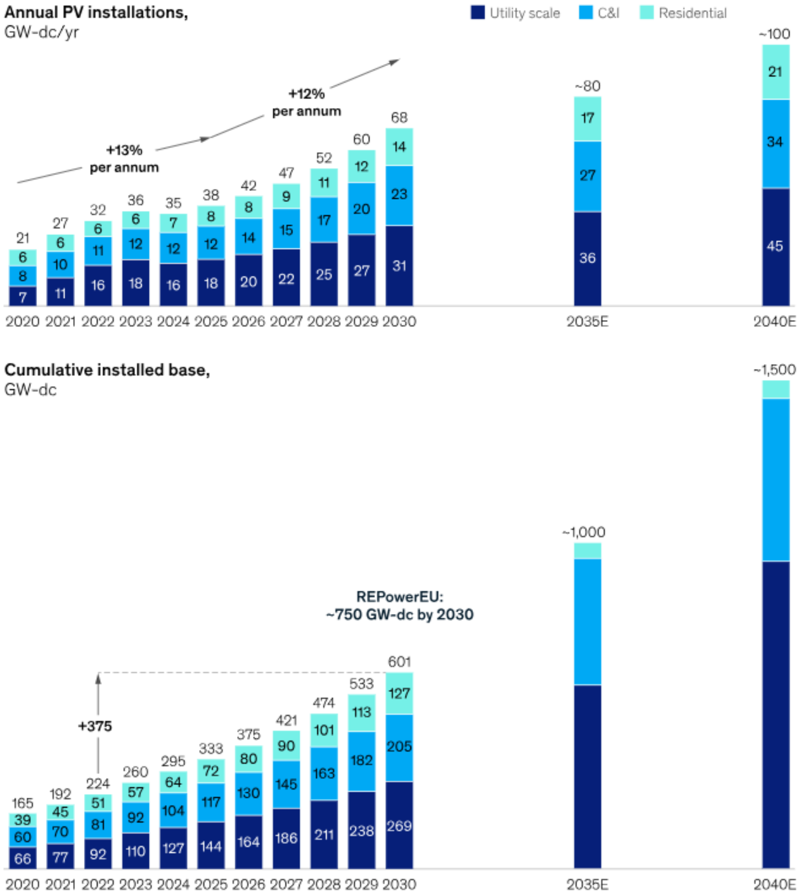


Figure 1.20: Scenario on PV installation following *EU solar energy strategy* [15]

The expansion of Variable Renewable Energy Sources (VRES) like wind energy and PV, if not complemented with a proper grid support and expansion, could lead to several problems related to grid stability and curtailment of renewable power plants. Regarding the latter issue, in Figure 1.21 a chart from [17] is provided. The case of Germany is exemplary in this sense: curtailment continuously increased over the past decade, but this trend has stabilised since 2015. While most of the country's wind capacity is situated in the north, major industries and load centres are in the south, leading to a geographical mismatch between renewable generation and consumption. This mismatch results in curtailment, particularly when the country cannot export its renewable electricity due to limited interconnection capacity. While major grid investment decisions to strengthen the north-south corridor are still pending, Germany has implemented smaller-scale grid expansions. These have helped the country reducing onshore wind curtailment by 2%

since 2015, but offshore wind curtailment increased from less than 1% to around 8% over the same period.

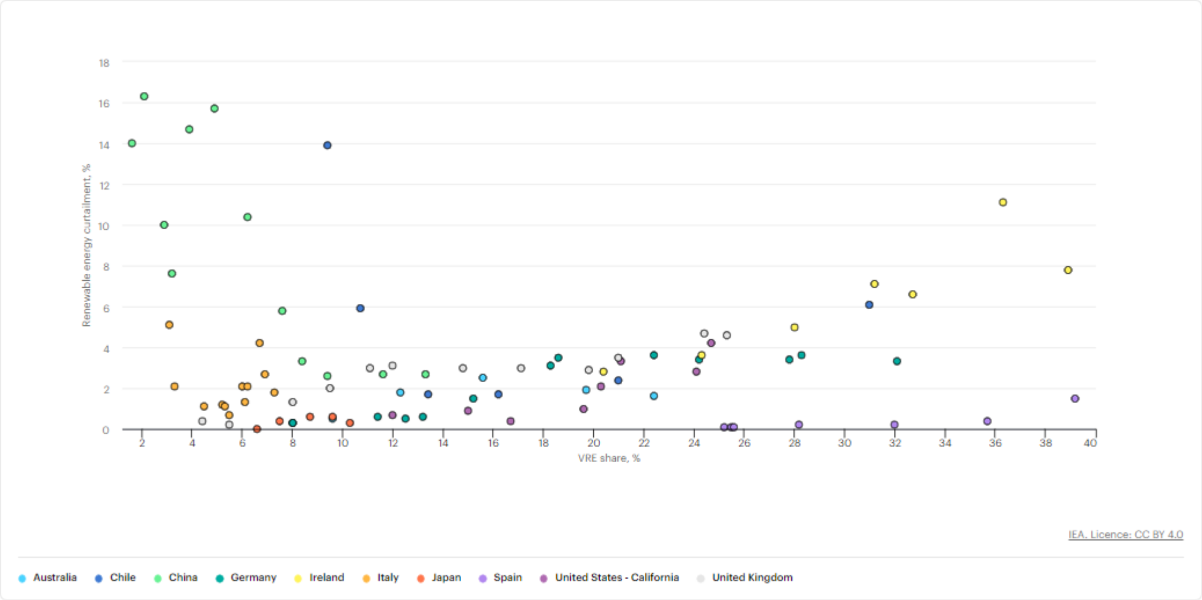
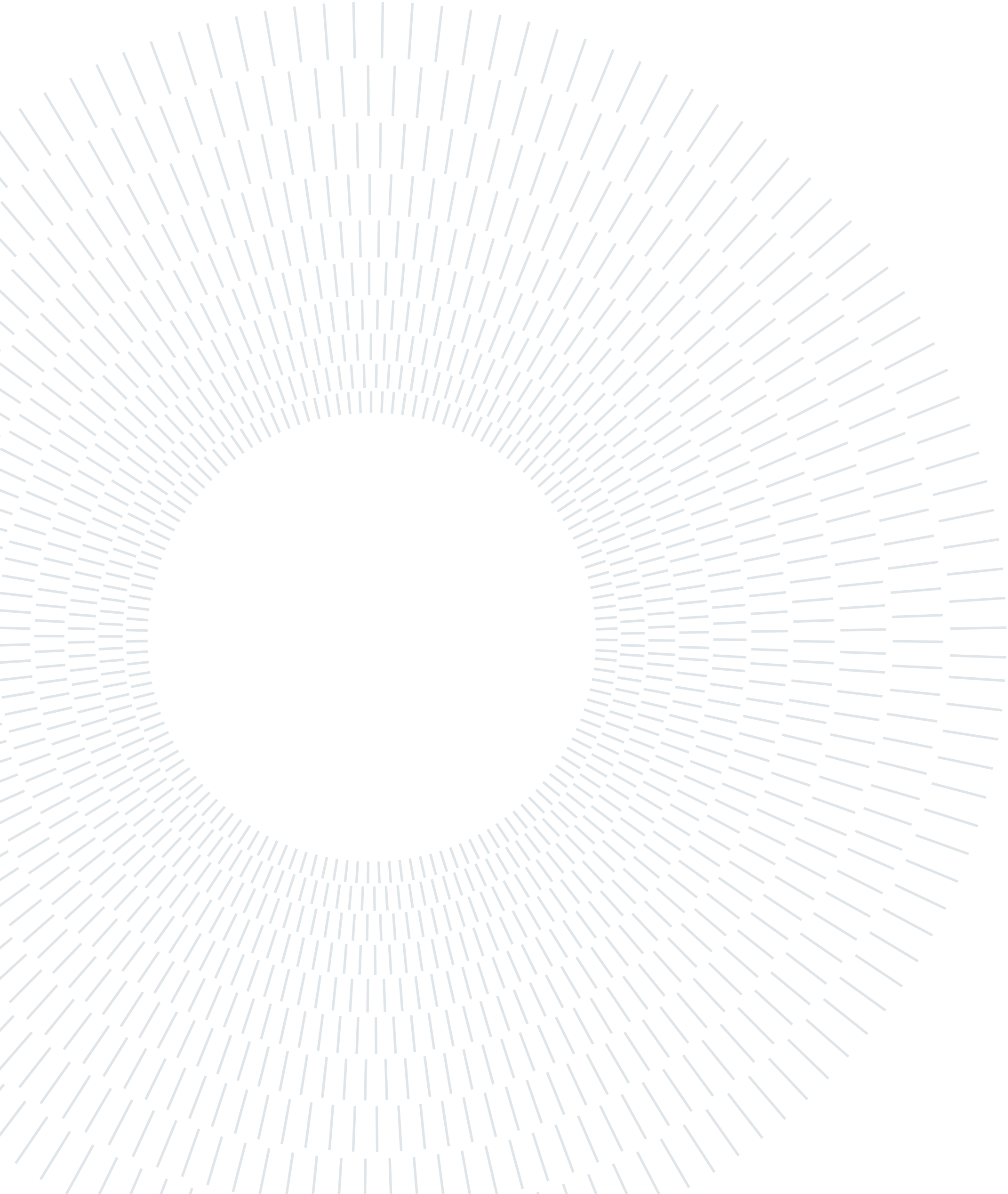


Figure 1.21: Renewable energy curtailment percentage per nation [17]

In light of the automobile sector situation and the evolution in energy markets, it appears of great interest to find a way to couple these trends and integrate EVs in ancillary services market. However, using a fleet of EVs as a distributed energy storage resource appears challenging mostly because of the difficulty in the evaluation of actual behaviour of single cars inside the fleet. This work aims to provide a general methodology that, starting from recorded data on mobility patterns, is able to determine the potential of EVs belonging to a certain geographical area to contribute to the provision of ancillary services to the grid, participating in energy markets.

The study starts with a literature review providing a detailed description of the players involved in the smart charging context and how they could participate to grid services provision, deepening rules and constraints for market participation. Then, similar studies are analysed to provide a context on the state of the art, highlighting strengths and weaknesses of each one of the works studied.

Then, the proposed approach is detailed and the quantitative results from the analysis are reported and discussed. Finally, conclusions and future improvements suggested are disputed in the final chapter.

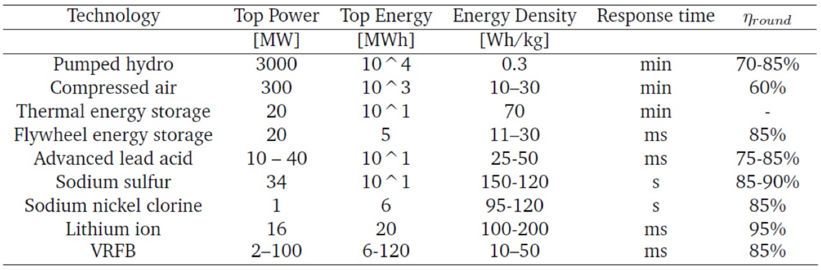


2 | Literature review

2.1. Vehicle - grid integration

Having acknowledged the raising diffusion of EVs in the last few years and looking at the trends for the upcoming future, it is clear how electrification of transport is a process that companies and policy makers can not ignore and that, if exploited with proper strategies, could present huge opportunities. As described in the report on grid integration of electric vehicles by IEA [9], developing and deploying technologies for e-mobility, could allow huge savings in terms of grid expansion and significant improvements in renewable energy exploitation.

To understand where the best opportunities for an aggregated EV fleet reside, it is essential to stand out the key features in the vehicle - grid interaction. As of today EVs are equipped with lithium-ion batteries, an electro-chemical storage technology that exploits the weak bonds between lithium ions and metal oxides to have a device able to store and then deliver back electric energy with high efficiency. Having no inertia related to thermal processes or rotating shafts, the response time of these devices is only related to mass transport phenomena and kinetics of reactions happening inside the cells, allowing to have times of response in the scale of few milliseconds. This characteristic makes lithium-ion storage particularly prone to fast reserve and in general typologies of services that require particularly short times of response. Figure 2.1 depicts a table comparing some of the key features for different storage technologies, while in Figure 2.2 the time and power scales of storage technologies in grid applications are reported.



Technology	Top Power [MW]	Top Energy [MWh]	Energy Density [Wh/kg]	Response time	η_{round}
Pumped hydro	3000	10 ^ 4	0.3	min	70-85%
Compressed air	300	10 ^ 3	10–30	min	60%
Thermal energy storage	20	10 ^ 1	70	min	-
Flywheel energy storage	20	5	11–30	ms	85%
Advanced lead acid	10 – 40	10 ^ 1	25-50	ms	75-85%
Sodium sulfur	34	10 ^ 1	150-120	s	85-90%
Sodium nickel clorine	1	6	95-120	s	85%
Lithium ion	16	20	100-200	ms	95%
VRFB	2–100	6-120	10–50	ms	85%

Figure 2.1: Key features of different storage technologies [18]

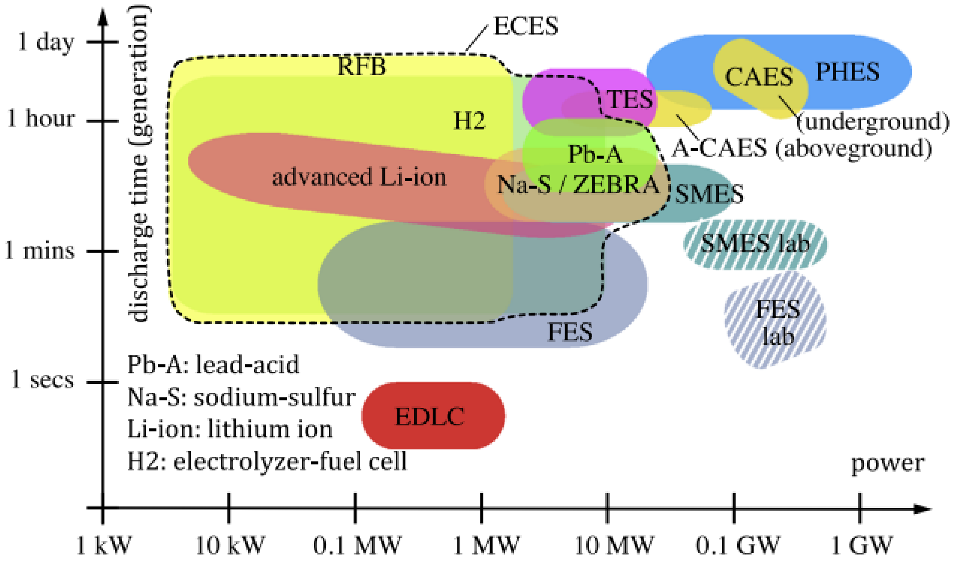


Figure 2.2: Time and power scales for storage technologies [18]

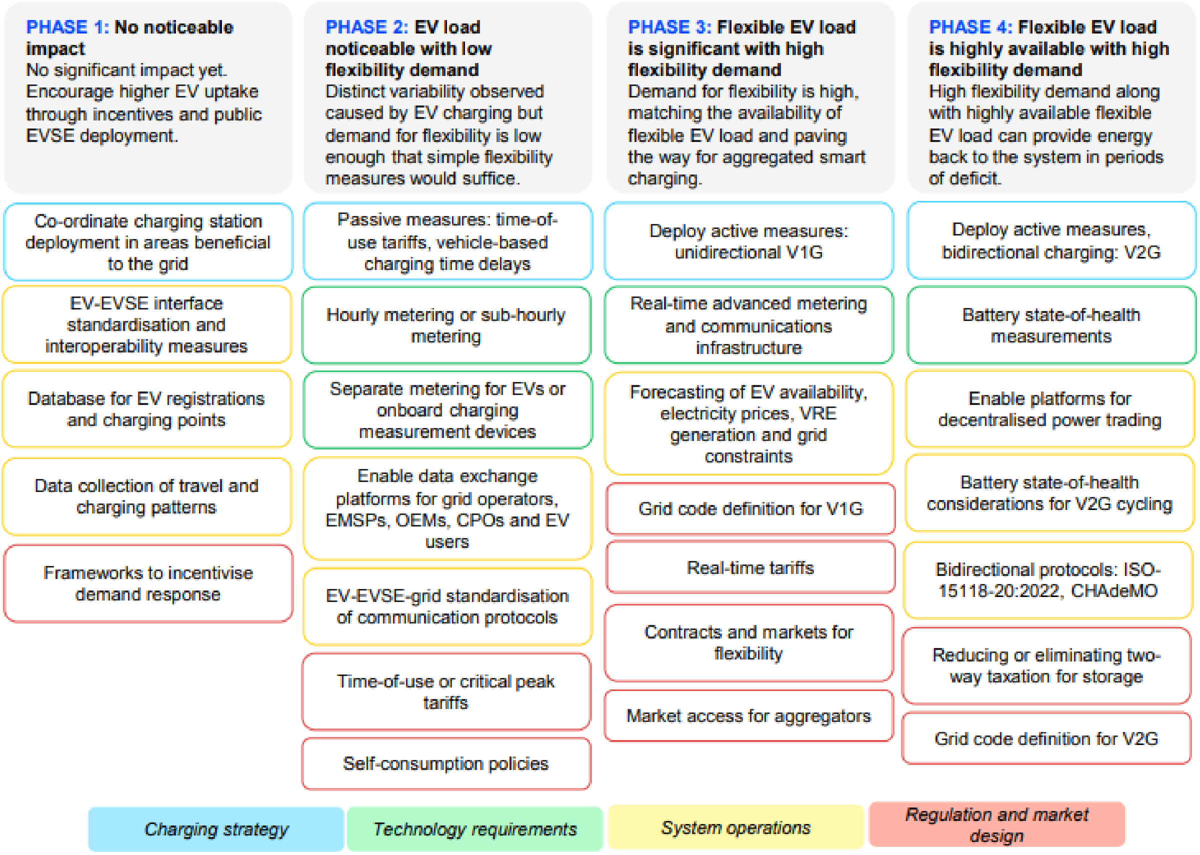
From the table above it is clear how li-ion batteries stand out for energy density and efficiency, characteristics that made them the preferred solution for automotive applications. The mentioned features, combined with the very fast response time could make li-ion batteries a truly interesting asset also for grid applications. What is currently hindering the adoption of this technology is its high cost that today is estimated to be around €15/kWh. To have an order of magnitude of how expensive this kind of application could be, the cost of the battery system could be approximated to the one related to capacity (it is neglected the fee related to the power delivery) and assess the cost of energy as the one of the battery system divided by the number of cycles in the lifetime times the efficiency of the battery, as described in Equation 2.1.

$$Electric\ energy\ cost = \frac{Storage\ Capacity\ Cost}{Number\ of\ Cycles \cdot Efficiency} \tag{2.1}$$

Since the cost of electricity is in the order of magnitude of €0.1/kWh to have a comparable cost, the number of cycles considering a lifetime of 5 years and a round trip efficiency of 90% for the storage system, should be of at least 1 cycle per day, so a really intensive use, hard to configure in the current grid scenario.

The main issue to be faced when offering flexibility services with an EV fleet is that the key goal of a vehicle is not the service itself, but allowing the user to move whenever he wishes. This makes hard to predict the charging EVs inside the pool and limits the mileage the user is willing to sacrifice to have a discount on the charge.

In Figure 2.3 the framework for vehicle - grid integration developed by IEA is reported. In such a dynamic and complex scenario as the energy sector is, it is necessary the simultaneous development of solutions in different contexts such as charging strategies, technology requirements, system operations, regulation and market design. To reach cost effective solutions that provide both a significant beneficial effect on grid operation and do not have a detrimental impact on final user mobility needs, it is essential that all the previously mentioned areas are properly addressed.



PHASE 1: No noticeable impact
No significant impact yet. Encourage higher EV uptake through incentives and public EVSE deployment.

- Co-ordinate charging station deployment in areas beneficial to the grid
- EV-EVSE interface standardisation and interoperability measures
- Database for EV registrations and charging points
- Data collection of travel and charging patterns
- Frameworks to incentivise demand response

PHASE 2: EV load noticeable with low flexibility demand
Distinct variability observed caused by EV charging but demand for flexibility is low enough that simple flexibility measures would suffice.

- Passive measures: time-of-use tariffs, vehicle-based charging time delays
- Hourly metering or sub-hourly metering
- Separate metering for EVs or onboard charging measurement devices
- Enable data exchange platforms for grid operators, EMSPs, OEMs, CPOs and EV users
- EV-EVSE-grid standardisation of communication protocols
- Time-of-use or critical peak tariffs
- Self-consumption policies

PHASE 3: Flexible EV load is significant with high flexibility demand
Demand for flexibility is high, matching the availability of flexible EV load and paving the way for aggregated smart charging.

- Deploy active measures: unidirectional V1G
- Real-time advanced metering and communications infrastructure
- Forecasting of EV availability, electricity prices, VRE generation and grid constraints
- Grid code definition for V1G
- Real-time tariffs
- Contracts and markets for flexibility
- Market access for aggregators

PHASE 4: Flexible EV load is highly available with high flexibility demand
High flexibility demand along with highly available flexible EV load can provide energy back to the system in periods of deficit.

- Deploy active measures, bidirectional charging: V2G
- Battery state-of-health measurements
- Enable platforms for decentralised power trading
- Battery state-of-health considerations for V2G cycling
- Bidirectional protocols: ISO-15118-20:2022, CHAdeMO
- Reducing or eliminating two-way taxation for storage
- Grid code definition for V2G

Charging strategy *Technology requirements* *System operations* *Regulation and market design*

Figure 2.3: IEA framework for grid integration of electric vehicles [9]

2.2. Smart charging market

In order to provide an exhaustive but still schematic description of the current smart charging environment, a brief description of the key stakeholders is presented in the following:

- Electric Vehicle (EV) user refer to the owner of an electrified vehicle that is able to connect to the grid, so as mentioned in Figure 1.3, BEVs and PHEVs.

- EV manufacturers or vehicle original equipment manufacturers (OEM) are companies whose business is producing vehicles. Currently the main players in the market are both worldwide historical carmakers like the Japanese Nissan, Europeans Stellantis Group and Volkswagen AG. New carmakers specialized in EV like the American TESLA or the Chinese BYD cover a relevant share of the market.

- Electric Vehicle Supply Equipment (EVSE) Manufacturers are the companies which produce EV chargers, whose function is to supply electric energy to recharge EVs. This EV charger consists of one or more electrical circuits and at least a single socket (or port/connector) per electrical circuit.

- Charge point operators (CPOs) run and maintain the charging stations. They do not necessarily need to own the charging infrastructure. Their tasks can be separated into technical (deployment, operation, maintenance) and financial (marketing, pricing), and both parts can be fulfilled by different entities. This business was originally formed and dominated by utilities but a high number of small, regional players are active in this field.

- Electric Mobility service providers (EMSPs) offer service contracts to end customers and provide the user interface for usage of charging infrastructure. Today, practical access to charging is mainly via radio frequency identification (RFID) cards and apps. A key success factor is to offer the end customer easy access to as many charging points as possible, regardless of the user's location. Historically, car manufacturers were front-runners in enabling long-distance e-mobility for their EV customers and offering additional services via the customer interface (cross-selling of other mobility services). However, as this is a software-intense business, many small, innovative IT start-ups have entered and now directly compete with OEMs (e.g., NewMotion, Plugsurfing, Virta).

- Aggregators are third-party entities that help aggregate various distributed resources, through EMSPs or CPOs, to act as middlemen to provide services to the power system.

- Distribution System Operators (DSOs) stands for the responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area. Where applicable, the DSO is also in charge for distribution grid interconnections with other systems, and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity.

- Transmission System Operators (TSOs) is the responsible for operating, ensuring the maintenance of and, if necessary, developing the transmission system in a given area. It is also liable for transmission grid interconnections with other systems, and for ensuring the long-term ability of the system to meet reasonable demands for the transmission of electricity.

- Electricity suppliers and retailers are companies supplying electrical power systems; suppliers offer electricity to the wholesale market while retailers in turn buy the offered energy and sell electricity directly to the consumers.
- Battery Manufacturers are companies producing the battery packs that equip the EVs. As of today the main players are the Chinese CATL and BYD, and the South Corean LG Energy Solutions.

The actors previously presented clearly have competing interests since their core business has the priority over the participation in a smart charging scheme. In fact, the ultimate goal is ensuring users mobility and this usually impose strict constraints on charging times and energy requirements. In Table 2.1 each of the key stakeholders previously presented is analysed and the major concerns and motivations are pointed out.

Stakeholder	Concerns and Motivation
EV Users	**Concerns:** Finding an available and functional charger, having enough autonomy for the next trip, privacy, and security. **Motivation:** Charging convenience, lower energy bills, and the desire for programs to manage EV charging that enhance these aspects.
EV Manufacturer or vehicle original equipment manufacturer (OEM)	**Concerns:** Handling warranty claims, charging convenience of clients. May engage in some programs to support charger deployment. **Motivation:** Sales and market share.
EVSE manufacturers	**Concerns:** Compatibility of electrical and communications features with vehicles, charge point operators, electric mobility service providers and the power system.
Charge point operator (CPOs)	**Concerns:** Securing grid interconnection and land acquisition; network tariffs. **Motivation:** Business model to increase charge point utilization and revenue streams.
Electric mobility service provider (EMSP)	**Concerns:** Interoperability of charge points for users. **Motivation:** Business model to maximize the share of subscribers.
Network/System operators (TSOs)	**Concerns:** Maintaining grid security and quality of electricity supply. **Motivation:** Obtaining revenue from public service provision under regulatory constraints.
Electricity suppliers and retailers	**Concerns:** Balancing their portfolios and ensuring that retail rates pay for the purchased energy. Suppliers, especially of variable renewable energy, have concerns about securing a buyer/off-taker to help reduce financial risk.
Aggregators	**Motivation:** Obtaining access to services where they can offer their contracted resources.
Battery manufacturers	**Concerns:** Availability and cost of materials. **Motivation:** Battery sales to vehicle original equipment manufacturers or subscriptions via battery-as-a-service.

Table 2.1: EV stakeholders' concerns and motivation [19]

2.3. Communication protocols

To enable EV aggregates to provide ancillary services to the grid is necessary that a clear framework for communication among all the involved parties is defined. In this section an overview about the state of the art in this area is provided, reporting definitions and uses of the protocols and standards currently adopted. [19] [20] [21]

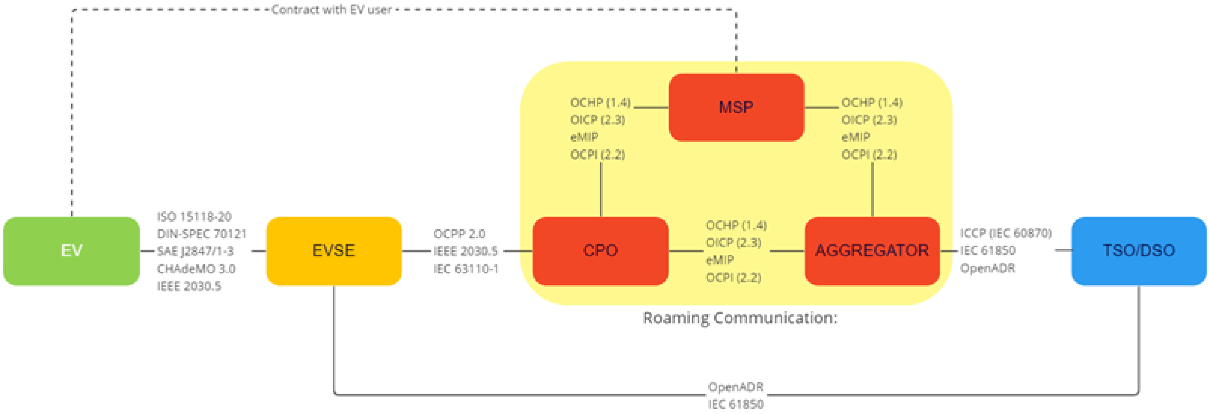


Figure 2.4: Map of players involved in the smart charging market and communication protocols

2.3.1. EV - EVSE communication

The communication between EV and EVSE can be divided in two different levels [22]:

1. Low level communication: voltage level and duty cycle information are used by the EVSE to establish if it is possible to proceed with the charging process and which is the maximum current level allowed.
2. High level communication: data regarding the compatibility, the charging schedules and sales tariffs, authorization and payment are exchanged. The principal techniques employed are:
    a. Power Line Communication (PLC): For the EVSE and EV communication IP-based protocols are used. PLC technology with a dedicated physical connection (CP, PE) is used for this purpose. In this system, the data stream is modulated onto the PWM signal. It is more familiar under the names Homeplug AV and IP-overpowerline in the consumer products field. In the vehicle's charge control module, a Transmission Control Protocol / Internet Protocol (TCP/IP) stack is used for communication. (PLC is used for high-level communication in CCS).

b. Signal Level Attenuation Characterization (SLAC): The SLAC mechanism of HomePlug Green PHY works according to the request/response method and it is compliant to ISO 15118-3 and DIN SPEC 70121. First, the vehicle sends a broadcast message and any EVSE that received this message (cross-talk) computes the signal strength and sends it back to vehicle. Then SLAC ensures that the vehicle and EVSE are physically connected by measuring the attenuation: the EVSE with the highest received signal strength is defined as the correct EVSE. The vehicle and charging station agree on a unique identification feature that must be contained in all subsequent messages of the same SLAC session. The SLAC protocol is supported by AUTOSAR basic software components.

c. Controller Area Network (CAN): CAN serves as a robust multi-master communication protocol tailored for rapid serial data transmission among electronic control units (ECUs). The protocol is structured around messages, which allows for efficient and flexible data exchange crucial for vehicle systems and manufacturing processes. In the context of electric vehicle charging, CAN is utilized for high-level communication in DC GB/T and DC CHAdeMO charging standards, facilitating the dialogue between the vehicle and charging infrastructure.

Standard	Focus	Use
ISO 15118	High-level communication, automatic authentication, authorization, load control, and billing procedures. Based on PLC with a HomePlug Green PHY communication protocol. Ready for V2G.	Global
SAE J2847/1-3	AC charging (part 1), unidirectional DC charging (part 2), V2G (part 3). Is based on SEP 2.0 and ISO 15118 and PLC	US
CHAdeMO	DC Quick charge based on ISO 61851 but using Controller Area Network (CAN) not PLC. Ready for V2G.	Global
GB/T 27930	V2G based primarily on SAE J2847, but with CAN based communication protocol following OEM practice of using ISO 11898	China
IEEE 2030.5	IP-based protocol used for the communication between EV and EVSE (i.e. front-end) in some R&D projects in the US (Chhaya 2015). Ready for V2G.	US

Table 2.2: EV - EVSE communication protocols detail

2.3.2. EVSE - CPO communication

The main protocols adopted in the connection between the EVSE and the entity that covers the role of the CPO are:

1. Open Charge Point Protocol (OCPP): has been designed and developed to standardize the communications between an EV charge point (also known as a charging station or charging equipment) and a central system, which is used for operating and managing charge points. The communication protocol is open and freely available to ensure the possibility of switching from charging network without necessarily replacing all the charging stations or significant programming, including their interoperability and access for electric grid services. The protocol is intended to exchange information related to transactions and for operating a charge point including maintenance.

2. IEEE 2030.5 Protocol: provides a framework for secure, manufacturer-agnostic communication. This protocol enables third-party operators to interact with customer-installed equipment, encompassing Energy Management Systems (EMS), photo-

voltaic (solar) systems, and EV charging stations. The design of this protocol is focused on ensuring interoperability across different manufacturers' products, facilitating secure exchanges of information and control commands among various components within the smart grid ecosystem.

2.3.3. Roaming communication

Since a single player could cover all the three roles is difficult to define a unique configuration and a precise flow of information. For sure a standardized communication among the players in this position of the market is crucial for the final users: if there is the need to charge the vehicle in a charging station that is not managed by the MSP (directly or through a CPO with whom it has a peer-to-peer contract) a standardized communication for authorization process and billing purposes is essential. In this area the main standards are: [23]

1. The Open Charge Point Interface protocol (OCPI) is designed for exchanging information about charge points. The protocol is for exchanging information between the market roles of Charge Point Operator and e-Mobility Service Provider. Is the only protocol not managed by a party that at the same time manages a roaming hub.

2. The Open Clearing House Protocol (OCHP) is a protocol which is meant for exchanging authorization data, charging transaction and charge point information data for roaming. The protocol is currently used with the e-clearing.net clearing house platform and consists of 2 parts:

    a. A part that is specifically for communication between market parties and an EV clearing house.

    b. A part that is for peer-to-peer communication between market parties, this is called OCHPdirect.

3. The Open InterCharge Protocol (OICP) is a roaming protocol created by Hubject in 2013, which can be used to communicate with the Hubject B2B Service Platform. This platform enables exchanging roaming messages between an EMSP and a CPO. Since 2016 the protocol consists of two parts that together create the protocol: a separate part for the EMSP and a separate part for the CPO.

4. The eMobility Interoperation Protocol (eMIP) is provided by the GIREVE organization. The main objective of GIREVE is: "open access to vehicle charging stations". The eMIP protocol targets the following goals (from the specification):

a. Enabling roaming of charging services by providing a charge authorisation and a data clearing house API.

b. Providing access to a comprehensive charging point database.

c. Providing smart charging features.

The above protocols aim to facilitate EV roaming between different parties by enabling the exchange of data needed for roaming transactions. The basic functionalities needed to support this are present in all four, namely authorization, billing, providing information on the charge point and charging session, and giving remote start/stop commands to the charge point. Furthermore, all protocols support real-time charge point status information (e.g., occupancy status). Some areas where we note interesting differences in functionalities include:

1. OICP does not offer peer-to-peer connections, and OCHP only does so in its 'direct' variant.
2. eMIP is the only protocol offering charge point search functionality.
3. eMIP and OCPI support real-time session information, OCHP only does so in its 'direct' variant, and OICP does not offer this feature.
4. OCPI is currently the only protocol supporting smart charging, though it does not seem unlikely that smart charging.
5. OICP, eMIP and OCPI use synchronous data exchange for authorization while OCHP relies on a synchronous approach (list of authorized subscribers updated as frequently as possible).

2.3.4. Aggregator – TSO

The main goal of protocols at this level is to provide to a centralized player that operates the grid information regarding flexibility opportunities and load scheduling, leaving the possibility to the grid operator to actively operate on downstream players to preserve the safety operation of the grid. A Capacity Bidding Program requires a bidirectional communication between customers (or aggregators) and the Utility. The OpenADR standard protocol is used as a communication method, as it includes a set of signals/events to implement DR programs, so it could be used to implement communication channels and establish the methods and format of information flow between the Utility and a customer/aggregator. The OpenADR protocol attempts to get an implementation of EI oriented to Demand Response (DR) management. OpenADR is structured as a network with no loops where each player is represented by a node. It allows Push and Pull modes, where the Virtual Top Node (VTN) can in the former initiate communication playing an active role while in the latter only receives information from the other nodes (Virtual End Nodes – VEN) [24] [25]

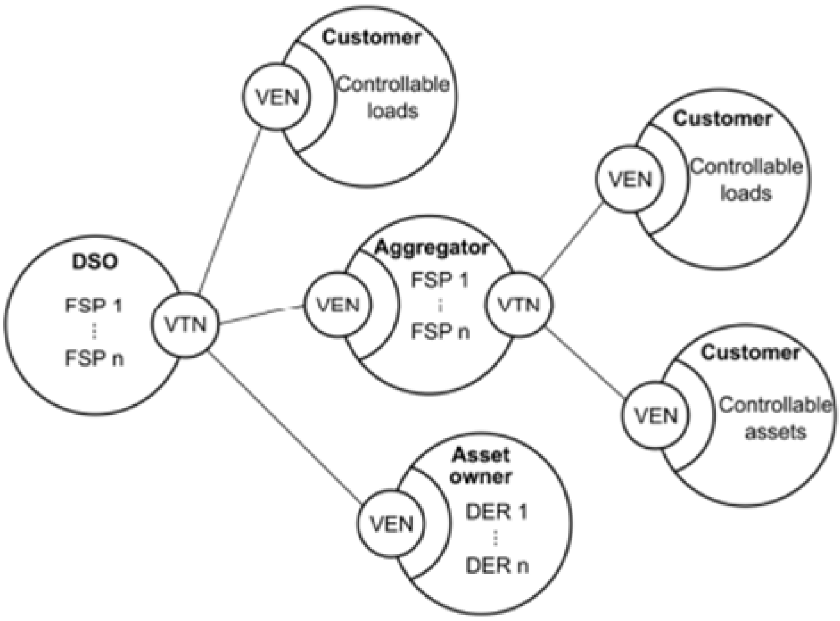


Figure 2.5: Graphic representation of VTN - VEN communications [25]

Inter-Control Center Communications Protocol (ICCP or IEC 60870/TASE.2): ICCP, also known as TASE.2, is a globally recognized standard for communications between control centers in the electric power industry. This protocol facilitates the sharing of data not only within a single utility's system but also across multiple utilities, power pools, regional transmission organizations (RTOs), independent system operators (ISOs), and non-utility power producers. The ICCP protocol enables the exchange of a vast array of information, including real-time and historical data, system statuses, measurements, scheduling information, operator commands, and more. Built upon the Manufacturing Message Specification (MMS or ISO 9506), ICCP supports both client and server roles and allows TCP/IP connections to be initiated in both directions, regardless of the client/server designation.

Power Line Communication (PLC) - IEC 61850 Standard: The IEC 61850 standard is dedicated to improving interoperability within the energy sector, particularly in the communication with substations and distribution systems. It specifies communication protocols for individual devices and establishes distinct data models for various types of equipment. IEC 61850, in conjunction with COSEM, is designed to be harmonious with the CIM data model, enhancing compatibility and integration across these three foundational data frameworks. The IEC 61850 standard is engineered to fulfill a range of System Use Cases (SUCs), including the collection of energy data, management of flexibility bids and activations, handling of sub-meter data, and the prediction of flexibility availability.

2.4. Pilot projects

Only a few pilot project are currently operative and the scale up of this technology is struggling mostly because of the economical difficulty in extracting value from the services provided to the grid and the complexity of the present market structure. A screening of the existing projects around the world is executed using *"V2G Hub"* [26] as a reference database.

Relevant aspects that are included in the analysis are:

1. The time span of the project
2. The number, nominal power and type of connector of the chargers employed. It is present also the information regarding the manufacturer of the charging equipment as "EVSE manufacturer"
3. The type of grid services tested
4. The number of vehicles and the car manufacturers involved
5. If present, the aggregator involved in the tests

For a significant part of the projects not all the information interesting for the research are available but looking at the reported data it is clear how the scale of all the projects is very limited: on a total of 116 pilot projects only 6 employed more than 50 chargers and less than 20 go beyond 10 charging points. Nissan is the most active car manufacturer and this is related to the fact that its model Leaf was one of the first to be enabled for smart charging thanks to its CHAdeMO compatibility. Companies that play the role of aggregators in these projects are truly various: from utilities like Engie or Enel to specialised companies like Nuvve or The Mobility House. The most tested services are the ones related to frequency regulation, that appear in half of the pilot projects that declare tests performed.

In Figure A.1 and Figure A.2, included in Appendix A the results of the screening are presented.

2.5. Electricity market

To get a proper understanding of the electricity market where smart charging services could be remunerated, an overview of the structure of Italian energy market is presented in the following.

The electricity market consists of the spot electricity market and of the forward electricity market. The forward electricity market is the venue where forward electricity contracts with delivery and withdrawal obligations are traded. The spot electricity market instead is where products with a closer delivery time are traded and consists of:

- Day-Ahead Market: *"Mercato del Giorno Prima" (MGP)*
- Intra-Day Market: *"Mercato Infragiornaliero" (MI)*
- Daily Products Market: *"Mercato dei Prodotti Giornalieri" (MPEG)*
- Ancillary Services Market: *"Mercato del Servizio di Dispacciamento" (MSD)*

The **Day-Ahead Market (MGP)** hosts most of the electricity sale and purchase transactions. In the MGP, hourly energy blocks are traded for the next day. Participants submit bids/asks where they specify a pair: the quantity and the minimum/maximum price at which they are willing to sell/purchase. The MGP sitting opens at 8 a.m. of the ninth day before the day of delivery and closes at 12 p.m. of the day before the day of delivery. The results of the MGP are made known within 12.58 p.m. of the day before the day of delivery. Bids/asks are accepted after the closure of the market sitting based on the economic merit-order criterion and taking into account transmission capacity limits between zones. Therefore, the MGP is an auction market and not a continuous-trading market. All the supply offers and the demand bids pertaining both to pumping units and consuming units belonging to foreign virtual zones that are accepted in the MGP are valued at the marginal clearing price of the zone to which they belong. This price is determined, for each hour, by the intersection of the demand and supply curves and is differentiated from zone to zone when transmission capacity limits are saturated. The accepted demand bids pertaining to consuming units belonging to Italian geographical zones are valued at the “Prezzo Unico Nazionale” (PUN – national single price); this price is equal to the average of the prices of geographical zones, weighted for the quantities purchased in these zones. GME acts as a central counterparty.

The **Intra-Day Market (MI)** allows market participants to modify the schedules defined in the MGP by submitting additional supply offers or demand bids. Trading on the MI takes place through the carrying out of three auction sessions *(MI-A)* and one continuous trading session *(MI-XBID)*. In the MI-A auction sessions, simultaneously with the negotiation of the purchase and sale offers, the intraday interconnection capacity is allocated between all the areas of the Italian market and the other geographic areas interconnected to the same involved in the market coupling. Supply offers and demand bids are selected under the same criterion as the one described for the MGP but, unlike in the MGP, accepted demand bids are valued at the zonal price. MI-XBID continuous session is divided into three phases. In these phases at the same time as the negotiation of purchase and sale offers, the intraday interconnection capacity between all the areas of the Italian market and the other geographical areas is allocated to the same interconnected active ones in the XBID. Bids and offers can be submitted per unit and per portfolio and for each phase of continuous trading of the MI-XBID, GME organizes a trading book by geographical and/or virtual areas and acts as a general counterparty.

The **Daily Products Market (MPEG)** is the venue for the trading of daily products with the obligation of energy delivery. The MPEG automatically admit all participants in the electricity market, trading in the MPEG takes place in continuous mode and allows trading daily products with:

- *"Unit price differential"*, for which the price indicated in the preparation of bids/asks and so the price determined on completion of the trading phase is the differential expression compared to the PUN, to which participants are willing to trade such products.
- *"Full unit price"*, for which the price indicated in the preparation of bids/asks and so the price determined as a result of the trading phase is the expression of the unit value of electricity exchange subject of the traded contracts.

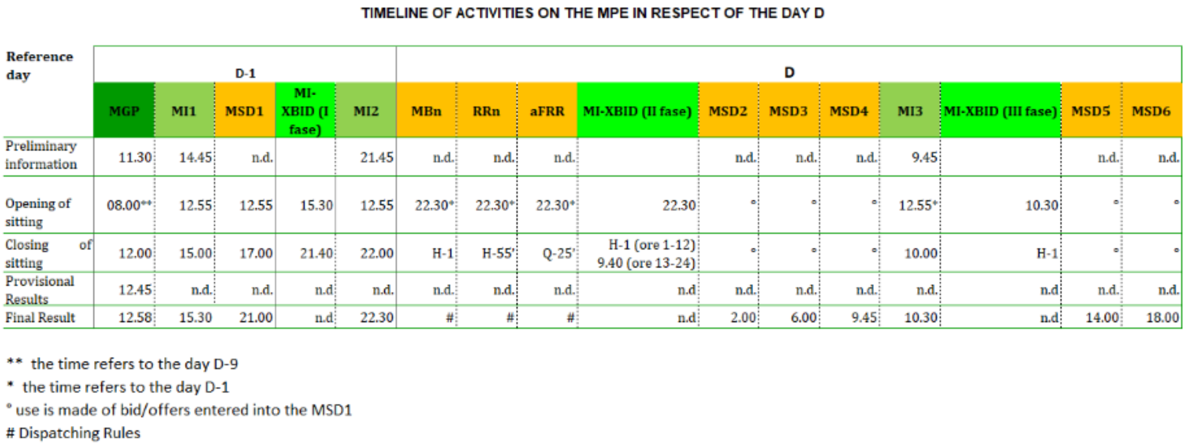
For both presented products in the MPEG are negotiable the following delivery profiles:

- Baseload, listed for all calendar days, whose underlying is the electricity to be delivered in all the applicable periods belonging to the day being traded.
- Peak load, listed for the days from Monday to Friday, whose underlying is the electricity to be delivered in the applicable periods from the ninth to the twentieth day belonging to the date subject of trading.

Participants of the electricity market that are also participants of the *"Piattaforma Conto Energia" (PCE)*, enabled to register translations on the electricity accounts available, can buy and sell daily products in the MPEG. The net electricity delivery position from the daily products trading exchanged in the MPEG is recorded in correspondent transactions in the PCE according to the modes set forth in the electricity market rules. The daily products currently traded in the MPEG are the products with the "unit price differential", with baseload and peak load delivery profiles.

The **Ancillary Services Market (MSD)** is the venue where *Terna S.p.A.*, the Italian TSO, procures the resources that it requires for managing and monitoring the system relief of intra-zonal congestions, creation of energy reserve, real-time balancing. In the MSD, Terna acts as a central counterparty and accepted offers are remunerated at the price offered (pay-as-bid). The MSD consists of a scheduling substage *“ex-ante MSD"* and *“Balancing Market" (MB)*. The ex-ante MSD and MB take place in multiple sessions, as provided in the dispatching rules Figure 1.18.

- The ex-ante MSD consists of six scheduling substages, while the sitting for bid/ask submission is a single one.
- The balancing market consists of the continuous submission of offers, with hourly readings for the 24 hours of flow day D. Opening of the session for the submission of offers for the Balancing Market is at 10.30 pm on the day before flow day D. Market participants may submit offers up to 60’ before the start of the hour H to which these offers refer. For offers referring only to the energy exchange platform for balancing from the Replacement Reserve (RR Platform), the limit for the submission of offers by market participants is H-55’.



TIMELINE OF ACTIVITIES ON THE MPE IN RESPECT OF THE DAY D

Reference day	D-1					D										
	MGP	MI1	MSD1	MI-XBID (I fase)	MI2	MBn	RRn	aFRR	MI-XBID (II fase)	MSD2	MSD3	MSD4	MI3	MI-XBID (III fase)	MSD5	MSD6
Preliminary information	11.30	14.45	n.d.		21.45	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	9.45		n.d.	n.d.
Opening of sitting	08.00**	12.55	12.55	15.30	12.55	22.30*	22.30*	22.30*	22.30	°	°	°	12.55*	10.30	°	°
Closing of sitting	12.00	15.00	17.00	21.40	22.00	H-1	H-55'	Q-25'	H-1 (ore 1-12) 9.40 (ore 13-24)	°	°	°	10.00	H-1	°	°
Provisional Results	12.45	n.d.	n.d.	n.d	n.d.	n.d.	n.d.	n.d.	n.d	n.d.	n.d.	n.d.	n.d.	n.d	n.d.	n.d.
Final Result	12.58	15.30	21.00	n.d	22.30	#	#	#	n.d	2.00	6.00	9.45	10.30	n.d	14.00	18.00

** the time refers to the day D-9
* the time refers to the day D-1
° use is made of bid/offers entered into the MSD1
Dispatching Rules

Figure 2.6: Timeframe for Italian electricity market sessions [27]

The resources that Terna needs for ensuring grid security can be obtained from the BSPs (Balancing Service Providers) through a series of a series of dedicated products. The provisioning method could vary from impositions, which may or may not be remunerated, or through the MSD, which is the preferable solution where competition exists.

In Table 2.3, a table that summarises available products for grid control and the current remuneration method is reported. With UPs it is meant *"Unit of Production"* and as it can be noted, most of services are currently provided by qualified UPs that are defined as plants with a power output above 10 MW. The growing adoption of renewable energy in the form of distributed sources, coupled with the potential phase out of traditional thermal power plants, highlights the rising demand for varied providers of ancillary services. Within this scenario, researching the role of EVs fleets as providers of ancillary services becomes increasingly relevant.

These trends could lead to a larger market, where smaller players will be more involved in the provision of ancillary services. Impositions from the TSO to large plants will likely reduce in favour of a stronger competition among market participants.

Service Class	Ancillary Services	Qualified Resources	Provisioning Methods	Remuneration
Frequency regulation	Primary reserve	Mandatorily qualified UPs	Obligatory	Optional
	Secondary reserve	Mandatorily qualified UPs	MSD	Pay-as-bid [€/MWh]
	Tertiary reserve, rotating, replacement	Mandatorily qualified UPs	MSD	Pay-as-bid [€/MWh]
	Balancing	Mandatorily qualified UPs	MSD	Pay-as-bid [€/MWh]
Compliance with operational limits on network elements	Congestion resolution in programming phase	Mandatorily qualified UPs	Obligatory	None
	Primary regulation	Mandatorily qualified UPs	Obligatory	None
Voltage Regulation	Primary regulation	Mandatorily qualified UPs	Obligatory	None
	Secondary regulation	Mandatorily qualified UPs	Obligatory	None
Additional services for electrical system security	Load shedding	UC	Dedicated auctions	System marginal price [€/MWh/year] + Pay-as-bid [€/MW] for interruption and for detached power
Emergency	Load refusal for UPs $>$ 100 [MW]	Mandatorily qualified UPs	Obligatory	None
Restoration	System re-energization after a black start	Mandatorily qualified UPs	Obligatory	None

Table 2.3: Ancillary services overview

2.6. Frequency regulation services

In Figure 2.7 it is presented an overview of timescales of the most relevant grid services. Given the extremely short response times that batteries are able to reach, this study will focus on the provision of frequency control services.

Frequency responsive reserve services act to slow and arrest changes in frequency via rapid and automatic responses that increase or decrease output from generators available for these services.

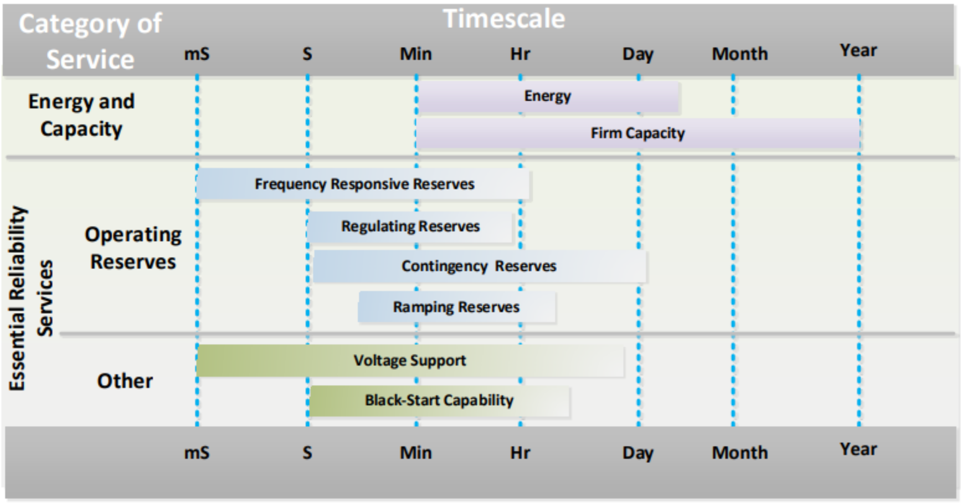


Figure 2.7: Timescales of grid services [28]

In order to keep the expected operating conditions and supply energy to all the users (loads) connected it is crucial to keep grid frequency inside tight boundaries to avoid unexpected disturbances that can create problems to the connected loads or even cause the system to fail. The most commonly used nominal frequency (Fn) in power systems is 50 Hz (Europe and most of Asia) and 60 Hz (North America). Reasons for this choice are based on technical compromises and historical situations. Generally, when the system operates in a range of frequency Fn±0.1 Hz, it is in the standard conditions, while when the frequency ranges from 47.5 to 51.5 Hz (in 50 Hz network for example), it is called emergency condition or restoration condition. These values may change from country to country. Frequency variations in a power system occur because of an imbalance between generation and load. When the frequency value reaches the emergency condition, the control strategy is initiated. The frequency control is divided in three levels: primary, secondary and tertiary controls. Each frequency control has specific features and purposes.

The primary control (or frequency response control) is an automatic function and it is the fastest among the three levels, as its response period is a few seconds. When an imbalance between generation and load occurs, the frequency of the power system changes. For example, with a load increase, the generated power does not immediately change, so the energy to compensate for this load increase arrives from the kinetic energy of the rotating generators that start decreasing the velocity (this is called the inertial response). After this moment, the speed controller (called the "governor") of each generator acts to increase the generation power in order to recover this kinetic loss and try to clear the imbalance. Generally, in about 30 seconds, each generation unit shall be able to generate the required additional power and then keep it for at least 15 minutes (this timing depends on the requirements of the transmission system operator). All the generation plants connected in the high voltage power system are called to supply this service, except the non schedulable renewable energy sources like wind, solar, biogas and hydraulic flow water. For this reason each generation unit shall have a dedicated and proper "reserve" power in order to accomplish this regulation when active. The purpose of the primary regulation is to clear the unbalance between generation and loads, in order to take the system to a stable condition. This service is mandatory for all the generators entitled to provide it and currently not remunerated. Regarding the not schedulable RES, these generators must be able to work with a defined P(f) function, in order to modulate their power according to the frequency value. This is easier in case of over-frequency, which requires power decrease. However, it could be really complex (almost impossible) in case of under-frequency, which would require a power increase, not always possible (even with a reserve power) due to the volatility of the primary resource itself. The continuous growth of RES implies the reduction of thermoelectric plants in operation, with consequent difficulties to perform this frequency regulation, for the reasons explained above. There are already different solutions under analysis and some of them already in place in several power systems (battery energy storage systems are one of the most promising). This is one of the main challenges to the massive deployment of RES in the power systems.

Once the primary regulation accomplished its target, the frequency value it's different from the nominal one, the reserve margins of each generator have been partially used and also the power exchange between the interconnected power systems is different from the predefined one. So, it is necessary to restore the nominal value of the frequency, the reserve of each generator previously used, and the power exchange among the power systems. This is the purpose of the secondary control. In order to perform this task, there are some generators entitled to perform the secondary control, through a dedicated reserve power. This reserve depends on the requirement of each TSO and usually, it is a percentage of the maximum power available, with a predefined minimum value to guarantee independently from the maximum power of each generator. If the frequency value is less than the nominal one, additional generation capacity needs to be started, while if the frequency value is higher than the nominal one, some generation capacity must be stopped, or the load has to increase. The secondary control is usually performed in an automatic way, by all the generators that participate to this regulation, through specific "set-points" sent by a central controller.

After secondary control is completed, the reserve margin used for this control shall be restored too and this is the purpose of the tertiary control (or replacement reserve), the last level of frequency control. In order to perform this restoring, the TSO sends single producers (even the ones not involved in the secondary control) the operating prescriptions related to power variation for the generators already in operation and, if needed, ask to start-up generators not operating at that moment. This control level is not automatic but it is executed upon request from the grid operator, and its remuneration following the same rules of the secondary control. [29]

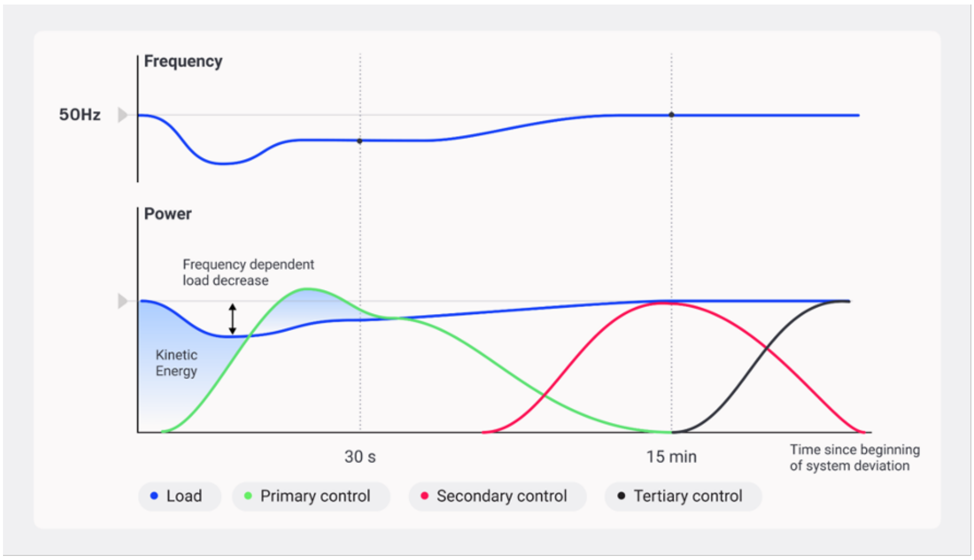


Figure 2.8: Intervention of different frequency control services [30]

2.7. Interruptibility service

In Italy, the interruptibility service is one of the tools that the TSO utilizes to ensure the safe operation of the electric system. When necessary, through its remote-control network, Terna directly intervenes on the breakers located in the production sites connected to the medium and high voltage network. This applies to sites with an average monthly power consumption of 1 MW or more per site, whose owners have subscribed to the interruptibility service.

For each MW of interruptible power made available, Terna compensates the service assignee based on the monthly consumption of the interruptible loads. This compensation consists of a fixed amount (for the availability of the service) and a variable amount (for each successfully executed interruption).

For what regards current regulation, all final customers holding withdrawal points, even when grouped in a consortium, including those with withdrawal points not connected to the grid but with an obligation to connect third parties, are eligible to participate in the procurement procedures for the instant interruptibility service. This is provided they meet the technical requirements for instant interruptibility as defined in the dispatching rules found in chapter 4 of the Grid Code [31], with an available interruptible power not less than 1 MW per individual site.

The offers from companies interested in the interruptibility program are selected through a marginal price auction held every three years; plus additional annual, intra-annual, and monthly auctions in case not all power has been allocated or if more is needed - starting from an annual unit compensation (referred to as the "reserve premium") of €105’000 per MW per year for the instant interruptibility service for the Continental Area and €126’000 per MW per year for the Sicily area and the Sardinia area. [32]

2.8. Regulatory framework for MSD participation

To clarify the role and the potentiality of the integration between EVs and grid, it is crucial to have a deep understanding of the regulatory framework currently in place regarding participation to balancing market for EVs in the area of interest.

According to what described in section 2.5, the MSD is ruled by Terna. An aggregated pool of EVs that can modulate its charging behaviour and is willing to participate to the MSD market is associated by Terna to an UVAM *“Unità Virtuali Abilitate Miste"*. From Terna’s documentation [33], an UVAM is an entity characterised by the presence of one or more elements belonging to at least one of the following categories: production units, accumulation systems and consumption units. In the context of V1G, EVs fall under the categories of interruptible consumption units, meaning a collection of loads connected to the public grid. Conversely, in the scope of V2G, with reference to the charging points where the EVs are connected, while charging they are totally comparable to storage systems.

In the following some of the key requirements to achieve the qualification of an EV pool as an UVAM are reported:

- Having at least hourly available and validated measurements on the connection point.
- All connection points must belong to the same aggregation perimeter as defined in the *“Annex 6 [26]”*.
- Each connection point associate to the UVAM must be equipped with a device that allows to get an analogical measurements called UPM *“Unità Periferiche di Monitoraggio"*, as in *“Annex 2 [34]”*.
- Regarding the qualification to offer secondary reserve both upward and downward, the "Enabled Upward Secondary Reserve Half-band" and the "Enabled Downward Secondary Reserve Half-band" must not be less than 1 MW in absolute value. With "Enabled Secondary Reserve Half-band" is meant the maximum raise/decrease of input that the UVAM can make available to Terna in any condition. [33]
- Concerning the qualification to offer secondary reserve only upward the "Enabled Upward Secondary Reserve Half-band" must not be less than 1 MW in absolute value while the "Enabled Downward Secondary Reserve Half-band" shall be equal to 2 kW. [33]
- About the qualification to offer secondary reserve only downward the "Enabled Downward Secondary Reserve Half-band" must not be less than 1MW in absolute value while the "Enabled Upward Secondary Reserve Half-band" shall be equal to 2 kW. [33]
- Creation and enablement of an UVAM can be done only with reference to the following services:
    a) Congestion resolution
    b) Rotating tertiary reserve
    c) Replacement tertiary reserve
    d) Balancing
    e) Secondary reserve
- UVAM must be able to modulate power injection and withdrawal following the manner and timing indicated in Chapter 4 of the Grid Code [31]

Once the UVAM is qualified it is significant to properly understand the procedures indicated to participate in the MSD, present the offers and execute the dispatching orders.

- The manager of the UVAM, named BSP *"balancing Service Provider"* is bound to execute the received dispatching orders and to communicate to Terna the *"Baseline"*, that is the power program for the points of the UVAM for the day. The baseline for day D must be communicated by 17.00 of the day D-1. It can be modified following the rules indicated in Chapter 4 of the Grid Code [31].
- The BSP must also communicate to Terna the distribution of power quantities among all the points belonging to the UVAM for each quarter of hour.
- The BSP is forced to present a predefined offer at the beginning of the operativity of the UVAM so that this offer can be utilised by Terna in case of the absence of a valid offer the day before the one the offers are referred to.
- The BSP can then present daily offers referred to the following day regarding the reserve allocation in the programming phase of MSD. In addition, the BSP can offer in the balancing market of the current day.
- For each hourly period in the MSD programming phase the BSP must present:

    a) at least one and up to four quantity-price couples on sale

    b) at least one and up to four quantity-price couples on purchase

  For all the offers the quantity must not be, in absolute value, lower than 1 MW.
- Regarding the remuneration for accepted offers Terna follows the directives indicated in *"Annex 22 [35]"* of Grid Code for what concerns the offers related to the MSD programming phase while the rules indicated in *"Annex 23 [36]"* of the Grid Code describes remuneration methods for offers concerning balancing market.

The secondary reserve service requires, as just exposed, participants to be authorized, meaning they must demonstrate reliability and accuracy in service delivery. Most importantly, it requires an automatic device capable of receiving the so-called "level signal" and implementing it, within a certain time frame, on the generators.

Given that in the case of an EV aggregate, the connection points consist of a relevant number of limited power charging stations, the cost of such an "actuator", to be implemented in each charging spot would be prohibitive. For this reason secondary reserve is not included in the proposed analysis.

2.9. Zonal unbalances regulatory framework

Each participant in the electricity market is required to submit its production/consumption plans in advance (the day ahead). Then in real operation, unbalances can occur and are defined as the difference between the actual production/consumption and the planned one.

The occurrence of an unbalance in a single unit is not necessary something detrimental for the grid, in fact the impact is strongly dependent on the *"zonal unbalance"* which is the total unbalance computed as the sum of all the unbalances of the single production and consumption units belonging to a specific zone. If the unbalance of the single unit has the same sign of the zonal one, it means the plant is exacerbating the existing deviation. Conversely, if the sign of the unbalance of the unit is opposed to the zonal one the unit is actually relieving the unbalance. The TSO can adopt two different approaches when dealing with unbalances: the *"single princing algorithm"* or the *"dual princing algorithm"*. These two logic differ for how the amount of an eventual penalty is computed, as reported in Table 2.4 and Table 2.5.

	Unit Unbalance [+]	**Unit Unbalance [−]**
Zonal Unbalance [+]	Receives: min (average MSD price in decrease; MGP price)	Pays: min (average MSD price in decrease; MGP price)
Zonal Unbalance [−]	Receives: MAX (average MSD price in increase; MGP price)	Pays: MAX (average MSD price in increase; MGP price)

Table 2.4: Single pricing algorithm logic

	Unit Unbalance [+]	**Unit Unbalance [−]**
Zonal Unbalance [+]	Receives: min (min MSD price in decrease; MGP price)	Pays: MGP price
Zonal Unbalance [−]	Receives: MGP price	Pays: MAX (MAX MSD price in increase; MGP price)

Table 2.5: Dual pricing algorithm logic

From Table 2.4 and Table 2.5 it is clear how the *"dual princing algorithm"* is more penalizing for units that produce an imbalance, since if the imbalance has opposite sign than the zonal one, no penalty is applied while in the *"single princing algorithm"* if the signs of the unbalances are opposite the unbalanced unit can even benefit from its imbalance if the average price in the MSD is cheaper than the one previously granted in the MGP.

2.10. Literature review on similar studies

This section aims to provide a literature review to examine existing research that has investigated the impact of electric mobility on the electric grid. The focus is on the analysis of implications associated with the mass adoption of electric vehicles and grid stability, with particular emphasis on the methodologies used and the goals pursued in this field. The comprehensive exploration of the impact of widespread EV adoption on grid stability has not been extensively studied, underscoring the importance of a thorough examination of the current research landscape.

In the following some of the most relevant approaches in the mentioned field are reported, highlighting the strengths and weaknesses of each of them. This will set the stage for demonstrating how the proposed research seeks to contribute to advancements in the field.

2.10.1. Traffic simulation studies

One of the most challenging aspects in the development of large scale models for vehicle-grid interaction is the analysis of the behaviour of single vehicles belonging to EVs' fleet. All studies, like the presented one, that aim to model an aggregate of vehicles with a bottom - up approach must deal with this aspect.

The majority of researches in literature are limited only to a specific typology of user or urban area. For example [37] proposes an interesting study on the optimization between the spatial and temporal planning of electrified autonomous mobility on demand and renewable energy feeding into the grid. This study constructs a typical day for each vehicle using data sourced from the 2014 New York City taxi data. The collected information encompasses details such as pickup time, drop-off time, pickup location (origin), and drop-off location (destination), along with the distance of each trip. In Figure 2.9 is reported a graphic representation of passengers calls in the considered day.

Figure 2.9: Travels visualization for [37]

Clearly this kind of approach allows to have a very detailed and precise determination of when vehicles are moving and when they are parked and so available for a charging session. In addition, it permits also a precise computation of energy consumption and state of charge of each single vehicle. However, the huge limit is that this kind of evaluation can be performed only for mobility on demand, that covers a derisory percentage of the overall travels taking place in an area during a day.

Some of the most interesting studies which try to model all trips that actually take place in a typical day are based on the MATSim tool. Multi-agent Transport Simulation (MATSim) is an open-source framework for implementing large-scale agent-based transport simulation which is adopted to model the daily activities of all drivers. In [38] synthetic drivers are generated starting from a population sample built with the aid of a dedicated tool named “PopulationSim”. PopulationSim requires three data sets as an input: household and person’s samples with related socio - demographic attributes, and the marginal distributions of controlled variables. Moreover it utilizes the samples and marginal distributions to generate tables of people and households representing the entire population of the modeled region. Once the population has been generated a daily driving profile is assigned to each individual to simulate the traffic for the entire study area.

This approach has great potential since it leads to a synthetic database with detailed information on energy expenditures, state of charge and time scheduling of each single vehicle. The limit is that lots of data are required to obtain a true to reality database and in fact in the work analysed many probabilistic manipulations are made to adapt available data to the case study of interest.

To avoid unnecessary manipulation of data and minimise the assumptions made, the approach used in this study is to start from a database named *"Origin Destination Matrix"*, built from surveys on mobility. An interesting work in literature that adopt a close methodology for the traffic simulation is the one in [39], where authors have developed a spatial-temporal model (STM), integrating the transportation network into the electric grid. In **Figure 2.10** is reported a schematic representation on how traffic data were integrated in the analysis performed.

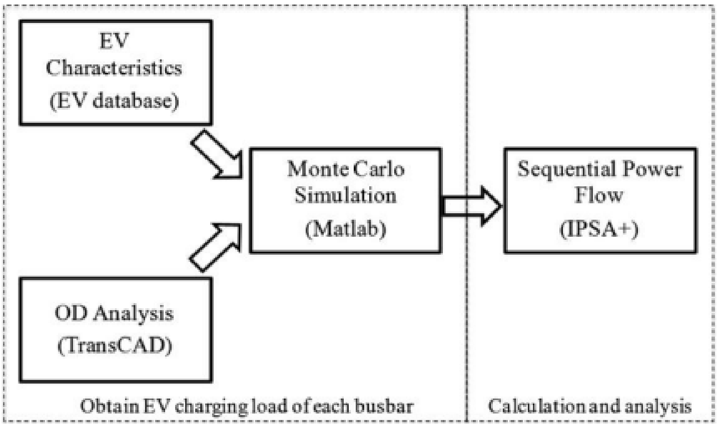
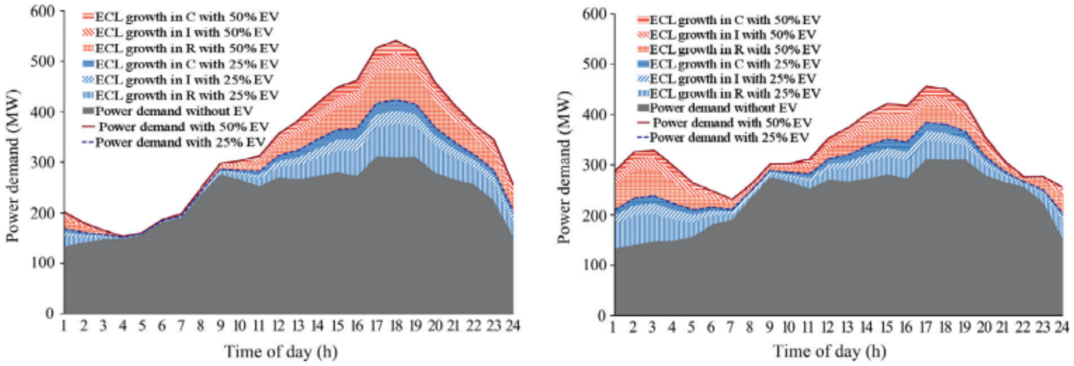


Figure 2.10: Traffic model methodology [39]

The main issue in this study is that the available travel matrix only provides information about the number of travels between zones, and it lacks information about the start time and intention of the trips. To make up for this lack of information probabilistic assumptions on starting time frames are made and also strong hypothesis on distances travelled are applied, neglecting the possibility of a change in the chosen path due to traffic conditions.

2.10.2. Impact on grid and services

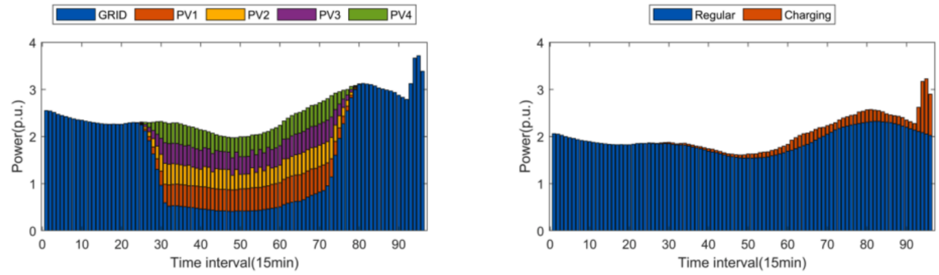
Once the various traffic simulations are performed, the next step of bottom-up mobility studies under examine is the evaluation of the impact of charging sessions on the grid and how to deal with them. Study in [39] mainly focuses on limit the detrimental effects that the added load from EV charging processes could cause on nodes of the distribution grid. To alleviate the stress from additional load the implemented idea is a smart charging scheme to obtain a *"peak shaving"* effect. Charging processes of each user are modified in order to still satisfy the energy demand at the end of the modelled day. Each vehicle can undertake a process of fast charging, slow charging, or delayed charging to limit stress on the distribution network. Results of this process are reported in Figure 2.11.



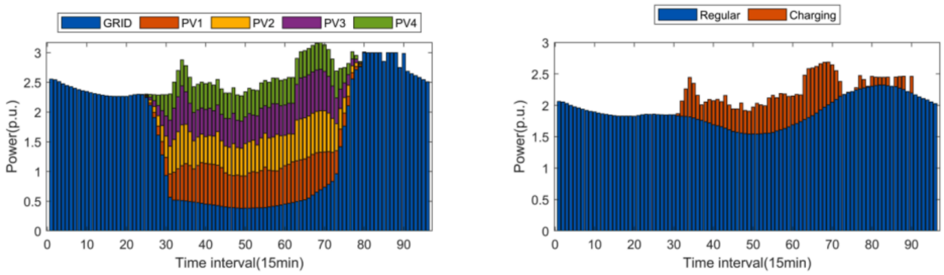
(a) Power demand with the "dumb" charging strategy (b) Power demand with the "smart" charging strategy

Figure 2.11: Results of [39] smart charging logic

Work in [37] focuses instead on the optimal coupling between charging sessions scheduling and renewable energy production. In particular, the developed algorithm aims to minimize the emissions from the vehicles of the autonomous taxi fleet by maximizing their uptake of energy in the hours when electricity production from PV plants is significant. The key constraint is that the customers' demand must be satisfied on time. Results of the simulation, reported in Figure 2.12, show a relevant flexibility of charging processes scheduling that allows a really good coupling between PV production and vehicles energy withdrawal.



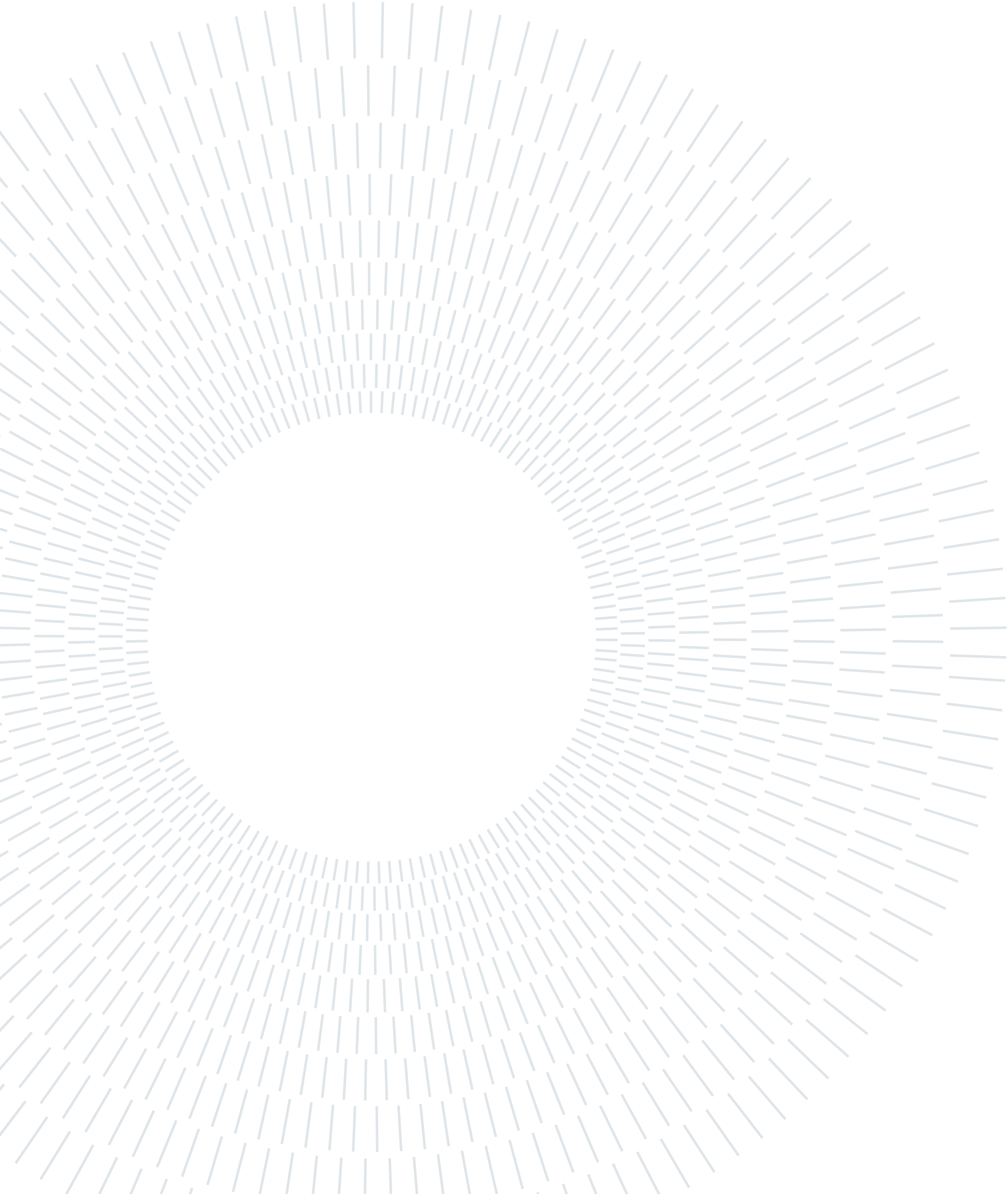
(a) Scenario 0: uncontrolled charging



(b) Scenario 1: controlled charging

Figure 2.12: Results of [37] EV - PV coupling algorithm

The investigated studies limit their analysis on the impact of charging processes on the grid or apply smart charging frameworks to limit these impacts or to match charging processes with renewable production. However none of the studies in object model the market participation of an aggregate and its potentiality in the offer of ancillary services. This is the main gap the presented work aims to bring a contribution to.



3 | Model and methodology

3.1. Goal and scope of the analysis

The goal of the analysis in this work is to assess the potentialities that an aggregate of EVs could have in terms of grid services offer. The developed methodology aims to be general and applicable to different contexts. The study focuses on e-mobility in Lombardy, establishing at first the impact of vehicles charging processes on the electrical grid and then the potential contribution of an aggregated pool of EVs to grid stability and the connected economical return.

To achieve this goal it is decided to build a bottom - up model, that starts from the single trips taking place inside Lombardy region, to establish the behaviour of the whole EVs pool. To perform a large scale analysis in the most realistic way possible, it is essential to start from data from a real case study. Data for this work are from a survey performed by *Regione Lombardia* [40] on mobility that will be better detailed in the following section. Starting from these data, it is essential to have a reliable model to assess the time windows when EVs inside the considered pool are plugged in and ready to deliver the required grid services. The model in object is the one developed in [41] that has been closely analysed with the developer and tuned for the use of interest of the research. Once the mobility model is solved, adding few assumptions on driver's behaviour and charging infrastructure availability, it is possible to estimate which travels are going to ask for charge and all the needed characteristic of charging processes (asked amount of energy, charging power, charging time...). Combining data describing single trips it is possible to derive the behaviour of the whole EVs pool and, in function of the desired service to be offered to the TSO, it is possible to determine the potential contribution the aggregator can offer.

In Figure 3.1 a flowchart describing the adopted methodology is reported. In blue are highlighted the input while in grey the relevant steps performed in the analysis.

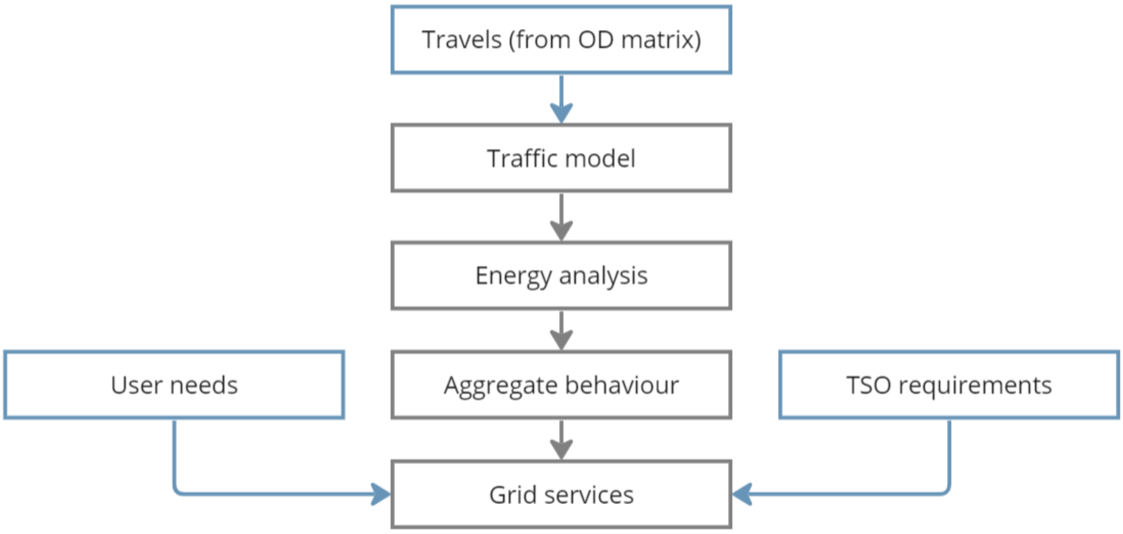


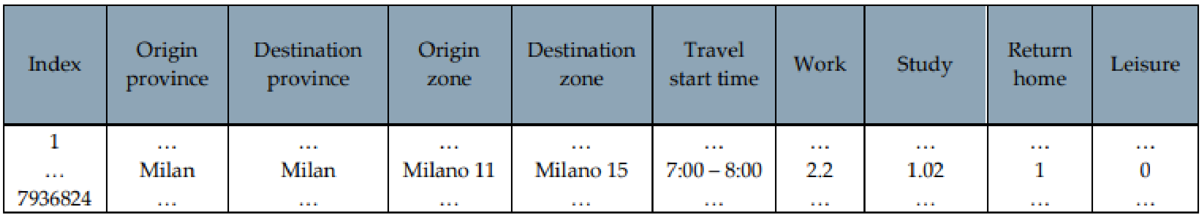
Figure 3.1: Methodology description

3.2. Input data and parameters definition

In order to simplify the comprehension of the methodology presented for the reader, it is chosen to enumerate and briefly present all the relevant parameters that will be used for the description. Elements listed in Table 3.2 represent the key parameters to define the core objects in the simulation: travels and charging points. The presented nomenclature will be used allover the work and the variables in the following will be reported in bold characters at every occurrence.

Variable	Description	Unit
Time Frame	time unit into which the day is divided	5 minutes (288 in a day)
Plugs In	time frame when the EV connects to a charging spot	x out of 288
Charging Start	time frame when the EV starts its charging process	x out of 288
Charging End	time frame when the EV ends its charging process	x out of 288
Charging Limit	time frame when the EV needs to leave the charging point	x out of 288
Charging Time	time frame when the EV starts its charging process	x out of 288
Stay Time	number of time windows between the arrival of the EV at the destination and the start of its next trip	[x ... x] out of 288
Power List	variable assuming in each position the value of 0 if the travel is not charging, the value of the charging power if a charging process is taking place	[x ... x] of 288 elements
Availability	variable assigned to charging points assuming in each position the value of 0 if the charging point is busy, 1 if the charging spot is available	[x ... x] of 288 elements

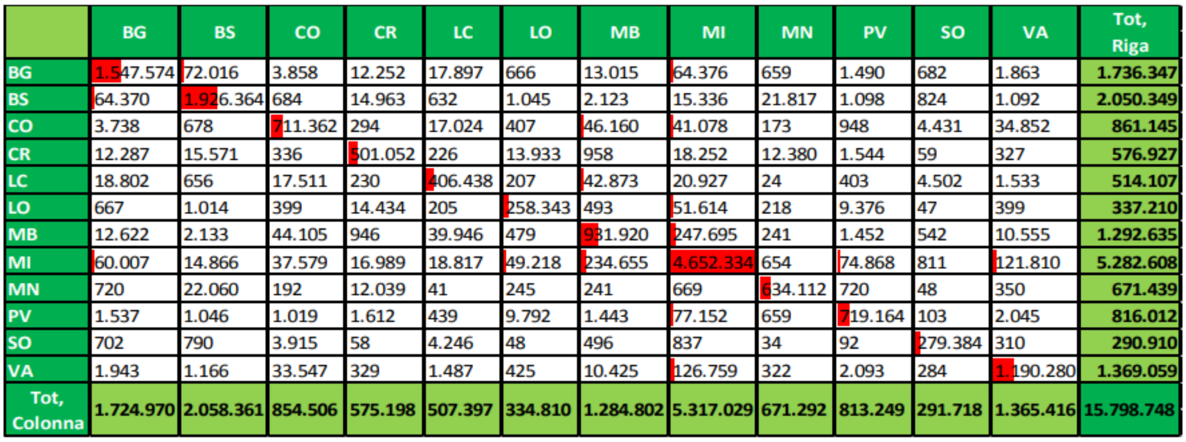
For the scope of this research data employed are from the Origin and Destination matrix created by *RegioneLombardia* [40], where a series of trips, representative of all travels taking place in a typical day, are collected. The data set is built based on a survey carried out by ISTAT, the Italian national institute of statistics. As can be seen in Figure 3.2, the data included in the matrix are: a province and the municipality of origin and of destination, a time frame (the hour of the day) in which the travel takes place and, for each reason of travel (study, work, return home and leisure) the number of travels corresponding to the defined characteristics.



Index	Origin province	Destination province	Origin zone	Destination zone	Travel start time	Work	Study	Return home	Leisure
1 … 7936824	… Milan …	… Milan …	… Milano 11 …	… Milano 15 …	… 7:00 – 8:00 …	… 2.2 …	… 1.02 …	… 1 …	… 0 …

Figure 3.2: Structure of the origin and destination matrix [40]

Figure 3.3 reports the number of travels collected in the origin and destination matrix from/to each province in Lombardy.



	BG	BS	CO	CR	LC	LO	MB	MI	MN	PV	SO	VA	Tot, Riga
BG	1.547.574	72.016	3.858	12.252	17.897	666	13.015	64.376	659	1.490	682	1.863	**1.736.347**
BS	64.370	1.926.364	684	14.963	632	1.045	2.123	15.336	21.817	1.098	824	1.092	**2.050.349**
CO	3.738	678	711.362	294	17.024	407	46.160	41.078	173	948	4.431	34.852	**861.145**
CR	12.287	15.571	336	501.052	226	13.933	958	18.252	12.380	1.544	59	327	**576.927**
LC	18.802	656	17.511	230	406.438	207	42.873	20.927	24	403	4.502	1.533	**514.107**
LO	667	1.014	399	14.434	205	258.343	493	51.614	218	9.376	47	399	**337.210**
MB	12.622	2.133	44.105	946	39.946	479	931.920	247.695	241	1.452	542	10.555	**1.292.635**
MI	60.007	14.866	37.579	16.989	18.817	49.218	234.655	4.652.334	654	74.868	811	121.810	**5.282.608**
MN	720	22.060	192	12.039	41	245	241	669	634.112	720	48	350	**671.439**
PV	1.537	1.046	1.019	1.612	439	9.792	1.443	77.152	659	719.164	103	2.045	**816.012**
SO	702	790	3.915	58	4.246	48	496	837	34	92	279.384	310	**290.910**
VA	1.943	1.166	33.547	329	1.487	425	10.425	126.759	322	2.093	284	1.190.280	**1.369.059**
Tot, Colonna	**1.724.970**	**2.058.361**	**854.506**	**575.198**	**507.397**	**334.810**	**1.284.802**	**5.317.029**	**671.292**	**813.249**	**291.718**	**1.365.416**	**15.798.748**

Figure 3.3: Summary of number of travels inside the OD matrix [40]

3.3. Traffic model

The main goal of the work in [41] is to develop a traffic model that, starting from the data contained in the origin and destination matrix and on the graph of the roads in Lombardy, could estimate, for a typical day, the travel time and the distance covered by each single travel. The developed methodology is able to take into account the congestion that could takes place in road network and accordingly adjust travel times. In Figure 3.4 a graphic description of the followed methodology is reported.

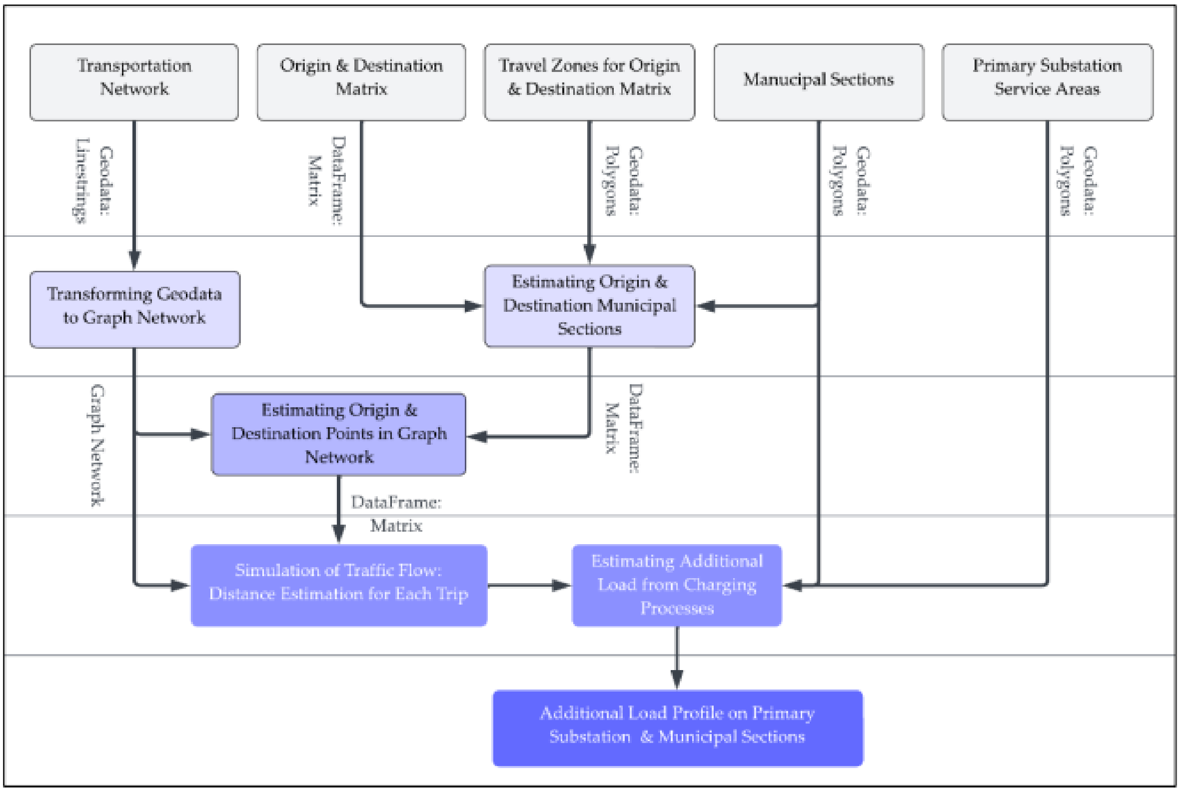
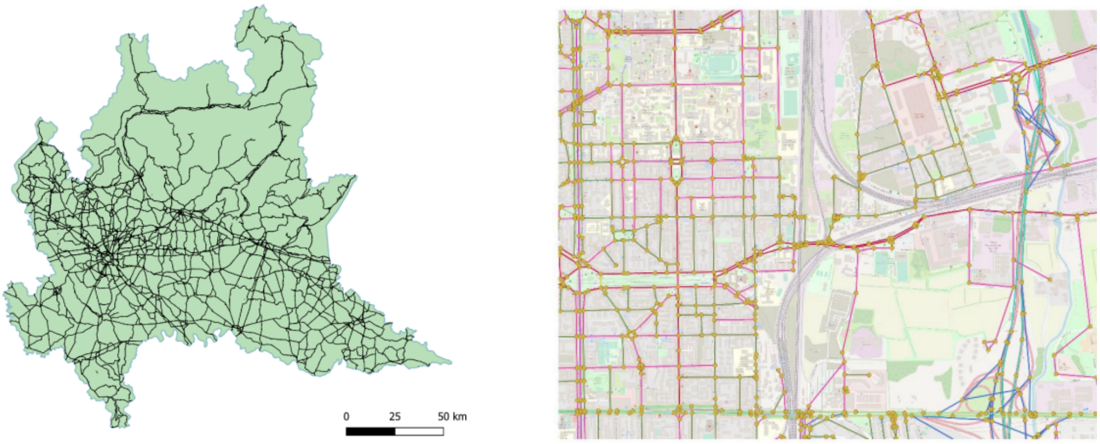


Figure 3.4: Procedure followed in [41]

The origin and destination matrix is manipulated and reordered to be properly integrated in the traffic model. The first step is to have a data set where each line corresponds to only one travel with all its properties and not the number of travels corresponding to a certain description as it is in the input data. This allows to ease all the following iterative processes to be operated. To improve the time granularity of the simulation, from hourly time windows the time step is reduced to five minutes. The analysis in the space dimension is performed including geographical data describing the relevant elements for the analysis, like roads, municipalities and areas reporting to each primary substation. To do so, shape files of previously listed elements relative to Lombardy are used.

Having now all relevant data in a proper form, it is possible to build a graph relative to the transportation grid. Firstly roads are filtered to keep only carriage ones and remove islanded road bits generated by the cutting process performed to account only for roads belonging to Lombardy. The result of the process is shown in Figure 3.5.



(a) Road network of Lombardy (b) Detail on Milan metropolitan area

Figure 3.5: Roads graph for Lombardy region on two different scales

The following step is to assign to each travel a specific origin and destination point inside the municipalities indicated in the origin and destination matrix. To do so a Montecarlo simulation is performed assigning to each municipal section a different probability that, depending on the type of travel, is influenced by parameters such as population, number of workplaces, parking spots and universities. Once start and end points are determined one last parameter to be set is the capacity of each road, that is evaluated as the number of cars passing through a section in a five minutes window at nominal speed. This parameter is crucial to properly assign penalties in terms of travel time when traffic congestion take place.

Once these steps are completed the traffic model is run: paths are determined using Dijkstra's shortest path algorithm, applying speed reduction coefficients that are function of the number of cars passing by a road. The algorithm works on travel times and not distances, so it is needed to evaluate a real travel time for each road. Roads are characterized by a nominal speed, a capacity and a length: every few travels the number of cars on each road is evaluated, than the correction factor is applied and finally a value of real speed is found. Once this latter value is available, dividing the length of the road bit by the real speed a real travel time is obtained. Dijkstra's shortest path algorithm then selects the available route with the lowest overall travel time, providing consequently of the arrival time. In Figure 3.6 a flow chart representing the working logic of the traffic model just described.

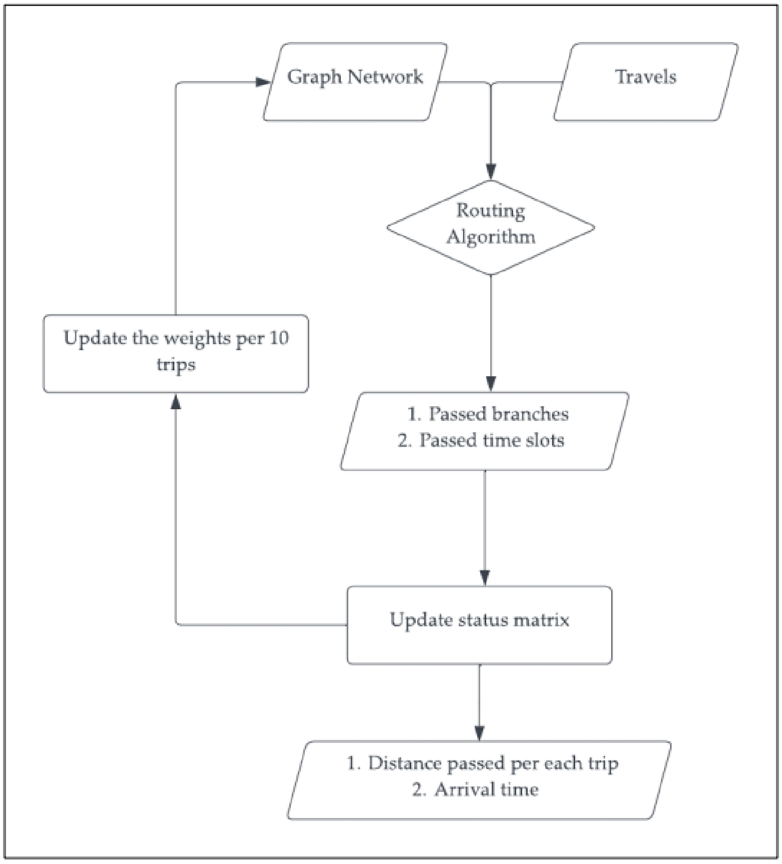


Figure 3.6: Traffic model flow chart [41]

The described approach allows to have a detailed model of all the trips taking place in a typical day. Start and end areas, together with start time frame, are directly taken from the OD matrix in input, with no further assumption applied, while routing and arrival time are the output of the shortest path algorithm that evaluates the fastest route taking into account the traffic conditions of the road network.

3.4. Selection of travels asking for charge

The first step to determine the feasibility and the potential of the application of a smart charging scheme in Lombardy is to provide an estimation of the load profiles generated by EVs' charging processes. To complete this step an energy analysis is built on top of the traffic model.

Firstly it is crucial to understand precisely how the output of the routing algorithm is structured, which are the useful data and which ones need a proper manipulation to be used. The database containing data with processed travels is constructed as reported in Table 3.1, where the key information for each travel are:

Travels	
Attribute Description	Example
Province of origin	MB
Province of destination	MI
Municipality of origin	MONZA 2
Municipality of destination	BUCCINASCO
Index that uniquely identifies the travel	1935626
Typology of travel (0: Work, 1: Study, 2: Return Home, 3: Leisure)	0
Assumed stay time in 5 minutes time windows	95 (7h 55m)
Start point on the graph	35459
End point on the graph	311401
Start timeframe (one of the 288 5m time windows in a day)	98 (08:10)
Travel duration in seconds	2736 (45m 36s)
Travel distance in meters	44719
Primary substation under which the travel destination is	52

Table 3.1: Data structure of traffic model output

The resolution of the simulation is chosen to be of five minutes time windows to have an effective granularity and to keep as close to reality as possible both the traffic simulation and the energy analysis. A further detail on the time scale would have resulted in an excessive computational burden without a significant improvement on valuable information extraction. Once the granularity is set, it is needed to ensure that all included data are coherent, so the travel duration has been converted from seconds to five minutes time frames, rounding to the closest integer. To identify the additional load profile created by EV charging, it's essential to isolate the EV related trips within Lombardy's overall travel activity. Then, from this subset, further identify the travels that require charging. The initial step involves establishing a scenario for EV penetration, followed by applying the determined percentage of EVs to the travel data set. To perform the selection a Monte Carlo simulation is run assigning to each province a different probability of hosting an EV travel based on current data on EV penetration [42]. In Table 3.2 the probabilities of finding an EV in each one of Lombardy's provinces are reported.

EV Probability											
BG	BS	CO	CR	LC	LO	MN	MI	MB	PV	SO	VA
11.4%	14.4%	7.4%	3.1%	3.8%	1.6%	3.2%	38%	8.9%	3%	1.7%	3.4%

Table 3.2: Probability of assigning an electric travel to each province in Lombardy

Once the 'Electric' travels are selected, the first parameter to be evaluated to perform the energy analysis is the energy expenditure related to each travel. The computation is performed by applying a coefficient of 0.2 kW/km to the travel distance attribute of the selected travels. This value is chosen as a meaningful average of current consumption of EVs on the market. [43]

Since it is not realistic that an EV owner charges his vehicle after every travel, a further distinction between travels performed by electric vehicles and travels performed by electric vehicles asking for charge must be done. From the data set containing *"electric"* travels, only travels that are asking for a charge must be selected.

To do so, a methodology to assign a probability to whenever a travel is going to ask for charge is set up. The assumption is that the higher is the energy consumption relative to the travel just performed, the higher is the probability of asking for charge. Applying this logic it is more likely that an electric vehicle that is coming from a long travel will be charged rather than one that has performed a short trip. Coherently, if the last trip was long the required amount of energy will be probably close to the one spent for covering the trip. However, not having information on the history of performed trips by that vehicle, there is still a possibility that a travel that has made a very short trip is going to ask for charge. In these cases, it would not be meaningful that the energy asked is close to the one just spent, but it is highly probable that if the travel is asking for charge the state of charge of the battery will be low. To implement this logic a progressive energy multiplier is applied to travels that spent less than 20 kWh in the last trip. In Table 3.3 an example of the application of this selection method is reported.

Attribute Description	Example 1	Example 2
Energy Spent	30.92 [kWh]	1.79 [kWh]
Probability of Asking for Charge	100%	2%
Energy Multiplier	1	10

Table 3.3: Example of selection logic for travels asking for charge

3.5. Definition of stay times

The first fundamental constraints to be set while defining the context for the application of a modulation algorithm on a pool of electric vehicle are the time boundaries within the charging process can take place. The lower limit is clearly set by the time frame when the travel arrives at its destination and can connect to the charging point. In the presented model this time frame is defined as the sum of the time window when the trip starts and the travel duration. Regarding the upper limit, the solution adopted in this study is to define a parameter named **stay time** that represents the time span over which each vehicle is assumed to be staying parked at the destination reached. These stay times are defined as normal distributions around a number of hours that is peculiar for each travel type. In fact, the hypotheses at the basis of this definition are that someone who moves for work reasons is likely to stay for around eight hours at his workplace, while somebody who travels for leisure reasons is probably going to stay parked at the destination for a much shorter time. In Table 3.4 the number of hours assumed to be the center of the normal distribution for stay times computation is reported for each travel typology.

Nominal Assumed Stay time for Travel Typology			
Work	Study	Return Home	Leisure
8h	6h	11h	4h

Table 3.4: Number of hours around which the normal distribution for stay times is set

Once the **stay time** is defined it is now possible to compute the **charging limit** time frame, as the sum of the time window when the travel arrives at destination and the assigned **stay time**. After all these computations each of the selected travels asking for charge is described with the parameters indicated in Table 3.5:

'Charging' Travels	
Attribute Description	Example
Province of origin	MB
Province of destination	MI
Index that uniquely identifies the travel	1935626
Typology of travel (0: Work, 1: Study, 2: Return Home, 3: Leisure)	0
Assumed stay time in 5 minutes time windows	95 (7h 55m)
Travel distance in meters	44719
Primary substation under which the travel destination is	52
Energy Spent	30.92 [kWh]
Timeframe when the EV arrives at destination	107 (08:55)
Charging limit timeframe	202 (16:50)

Table 3.5: Updated structure of information on travels

In white rows are reported the relevant information from traffic model output, useful for upcoming analysis. While the information highlighted in orange are added with the previously described steps. After this first analysis, the energy request value and the time boundaries for the start and end of the charging process are associated to each travel asking for charge.

3.6. Modelling of charging points

Until this point of the study no assumption on the number nor on the availability of charging points has been made. It is assumed that *Return Home* trips that require charging have a domestic charging point to connect to, where there are no availability issues. However, for public charging spots it is essential to have an estimation on both the parameters mentioned, since the actual possibility of each single vehicle to plug in and start the charging process has obviously a huge impact on the load profile generated by the EV pool.

To add this aspect to the analysis charging points are modelled as a *Python* dictionary variable structured as follows:

- As a key to access the dictionary is generated a variable of tuple type, so composed by two elements: the first is the province where the charging point is located, the second is a number that uniquely identifies the charging spot.
- The first information stored inside the dictionary is a variable named *Power*, an integer that reports the nominal charging power associated to the charging point.
- The second information is instead a list of 288 elements (one for each time window of the simulation) initially set to one named *Availability*. When a number in this list is one it means that the charging spot in question is *"free"* and available for a car that requires charging in that particular time frame. Instead, if a number is zero it means the charging point is *"busy"* because it is delivering energy to a vehicle and so it is unavailable for any other car.

In addition to setting the total number of public charging points in Lombardy, another wicked problem is how to distribute the charging points allover the region. It is reasonable that the number of charging spots closely follows the number of electric vehicles. For this reason the allocation of chargers performed in the presented work follows the same probabilities defined in Table 3.2 for the selection of travels performed by EVs in each province.

Finally, the remaining parameter to be set is the nominal charging power deliverable by each charging spot. Since the framework defined is modelling only travels inside the considered region, that are on average not much energy demanding and that do not require particularly short charging times as a particularly long highway trip might, fast charging processes are not included. High power fast chargers are consequently not modelled inside this work.

Table 3.6 reports a summary of the structure of a single item defining all the presented attributes for a charging point in the model.

Charging Point Description		
Key	Power	Availability
('BG', 123)	6 kW	[1, 1, 1, 1, 1, 1, ..., 1]

Table 3.6: Charging points model description

3.7. Construction of load profile

After having processed the output of traffic model and having modelled the charging points, it is possible to perform an energy analysis on the whole aggregate and evaluate the added load profile generated by the electric vehicles charging processes on the grid.

For the sake of computational speed and organisation of the data, the information regarding selected travels that are asking for charge which were contained inside a *Python Pandas "dataframe"* type variable are converted to a *dictionary* type variable.

The algorithm developed to perform the energy analysis scrolls through all the trips contained into the created *dictionary* and firstly analyse the travel typology since a different procedure is applied whether the trip processed is a *Return Home* travel or not. In fact, as stated in section 3.6, it is assumed that *Return Home* travels charge at private domestic charging locations, where no availability issues raise. To these charging points is assigned a nominal power output of 6 kW.

For *Return Home* trips the charging spot at the destination is assumed to be available: the charging process can start in the same time frame when the car reaches its destination and a power of 6 kW is attributed to the travel. The charging time is then computed as follows:

$$charging\ time = \frac{energy}{power} \cdot \frac{60}{5} \tag{3.1}$$

The second term of Equation 3.1 is needed to convert the result from seconds to five minutes time windows. The output is then rounded to the closest integer in order to have the integer number of five minutes frames needed to fulfill the energy request.

It is now possible to compute the time frame when the charging process ends as the sum of the charging start time window and the charging time just computed. During this process it is essential to put in place a control logic to check that the **charging end** happens before the **charging limit**. In case this is not verified the new **charging end** is set to be equal to the **charging limit** time frame.

After this check is performed, a similar logic is applied to the cases in which the **charging end**, the **charging limit** or both time frames fall beyond the daily limit of 288. When these cases occur, knowing that the python indexing for all the list variables used is from 0 to 287, it is necessary to subtract 288 from the numbers found so that the time frame in consideration is *wrapped up* to the first time window of the day.

After having set the limits of the charging process is essential to be able to precisely identify the time windows when each vehicle is undergoing a charging process. Since some of the charging sessions starts during the evening and ends the next morning it is crucial to distinguish the two cases when **charging end** time window index is greater than when **charging start** one (see Figure 3.7), from the ones when **charging end** has been *wrapped up* and so its index is lower than **charging start** one (see Figure 3.8).

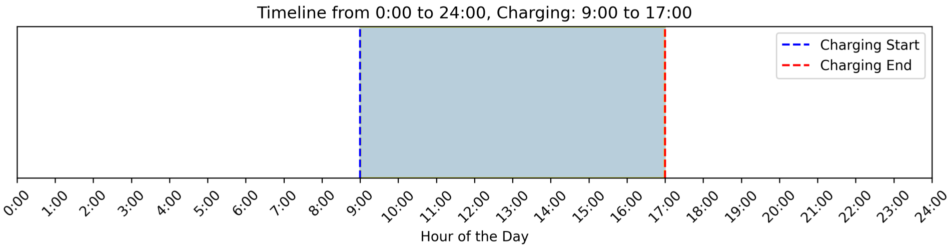


Figure 3.7: Timeline without wrap up

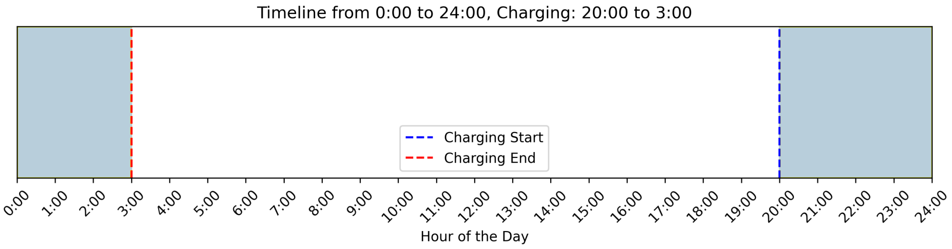


Figure 3.8: Timeline with wrap up

To be sure to have selected the correct time frames is clearly not enough to apply a condition where it is asked charging start $<$ time window $<$ charging end, but it is necessary to develop a mask that comprehends the logic described in the flow chart in Figure 3.9.

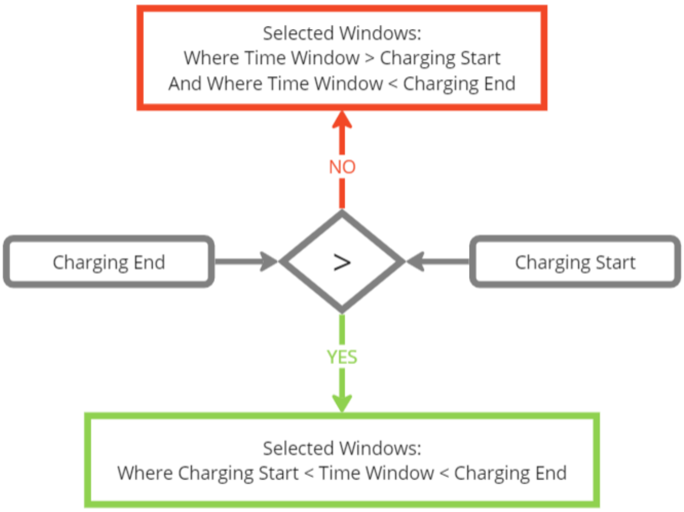


Figure 3.9: Mask for time windows selection

Having precisely selected the time windows when the vehicles are charging for each trip is defined a new attribute called **power list** that consists of a list variable with 288 elements, corresponding to all the time windows of the simulation. It contains zeroes where the trip is not charging and the value equal to the charging power for the time windows when the vehicle is undergoing a charging process.

Another aspect that is crucial to keep under control is whether each trip is able to fulfill is charging need or not. The previously presented mask is tuned to consider the time windows between **charging start** and **charging limit** time frames. This way it is possible to evaluate the maximum number of time windows the car can stay plugged in and so evaluate the achieved percentage of charge in the charging time as:

$$charge\ \% = \frac{time\ windows\ plugged\ in}{charging\ time} \cdot 100 \tag{3.2}$$

From Equation 3.2, it is clear how in case of a percentage greater than 100% the trip is able to fulfill its energy needs while if the percentage is lower than 100% its value is representing the portion of required energy the charging process was able to supply considering charge at nominal power.

In Algorithm 3.1 all the operations carried out for trips of type *Return Home* are summarised:

Algorithm 3.1 Load Profile Builder for *Return Home* travels

```
Assign a charging power of 6 kW
Compute the charging time needed to fulfill the energy request
Compute the charging end time frame
Make sure all time windows are inside the daily range and if not wrap them up
Apply a mask to identify time frames where the trip is charging
Create an attribute named power list containing a list with the charging power value
    in time windows when the travel is charging
Compute the percentage of the required energy the trip is able to charge in the time
    windows it is plugged in
```

The presented procedure is then customised and refined to manage the added complexity of charging spots availability for travels of the typologies *Work*, *Study* and *Leisure*.

Firstly, it is essential to establish which is the logic to be applied in case a trip does not find an available spot at its arrival. One viable option could be that if the charging point is occupied at the arriving time the travel simply does not charge. This option seems far from reality where the vast majority of mobility service providers (MSPs) offer an application where charging points can be booked. The user can have an idea about when the desired charging spot would be free and start consequently the charging process later on. Based on this latter consideration, the chosen approach delays charging start of travels that do not find a free charging spot until one in the same area is free. While applying this process it is essential to be sure not to overcome the limit defined by the maximum **stay time** of the trip. This logic of postponing the start of the charging process should include a further consideration: it would not be meaningful to plug in the car and charge for a few minutes because of constraints related to another booking in the charging spot or to the departure time. It is than needed to ensure that there are at least as many consecutive time windows as needed to fulfill the energy requirement of the trip.

When a travel which typology is different than *Return Home* is evaluated, the code scrolls the charging points (variable created as described in section 3.6) and checks if there is an available charging spot in the destination area for the arrival time frame, and if so it proceeds with an energy analysis similar to the one described for *Return Home* trips. One relevant difference to be considered is that the charging power this time is function of the assigned charging spot. The power is so picked from the appropriate attribute inside the variable associated to the selected charging point. The remaining computations are close the ones performed for *Return Home* trips. In Algorithm 3.2 the final part of the energy analysis is reported.

Algorithm 3.2 Load Profile Builder for *Other Types* travels

```
Compute the **charging time** needed to fulfill the energy request
Compute the **charging end** time frame
Make sure all time windows are inside the daily range and if not wrap them up
Apply a mask to identify time frames where the trip is charging
Create an attribute named **power list** containing a list with the charging power value in time windows when the travel is charging
Compute the percentage of the required energy the trip is able to charge in the time windows it is plugged in
```

After this first analysis the model checks if there are at least as many consecutive time windows as the computed charging time and if so the ID code of the charging point is associated to the travel as a new attribute and the availability of the charging spot is set to 0 (so not available) for the time windows when the evaluated trip is charging. If the condition is not satisfied, the code evaluates another charging point competing to the same area by repeating the procedure. If no suitable charging spot is found for the trip, the model postpones the charging start of one time window and repeats the whole search of an eligible point until the condition where **charging start** and **charging limit** coincide. If this happens, it means that for the whole duration of the stay there are no available time windows in the charging spots of the destination area that are suitable for the energy requirement of the trip analysed, so the travel is not able to charge.

Figure 3.10 presents a flowchart that aims to summarize and clarify the developed methodology that has just been exposed.

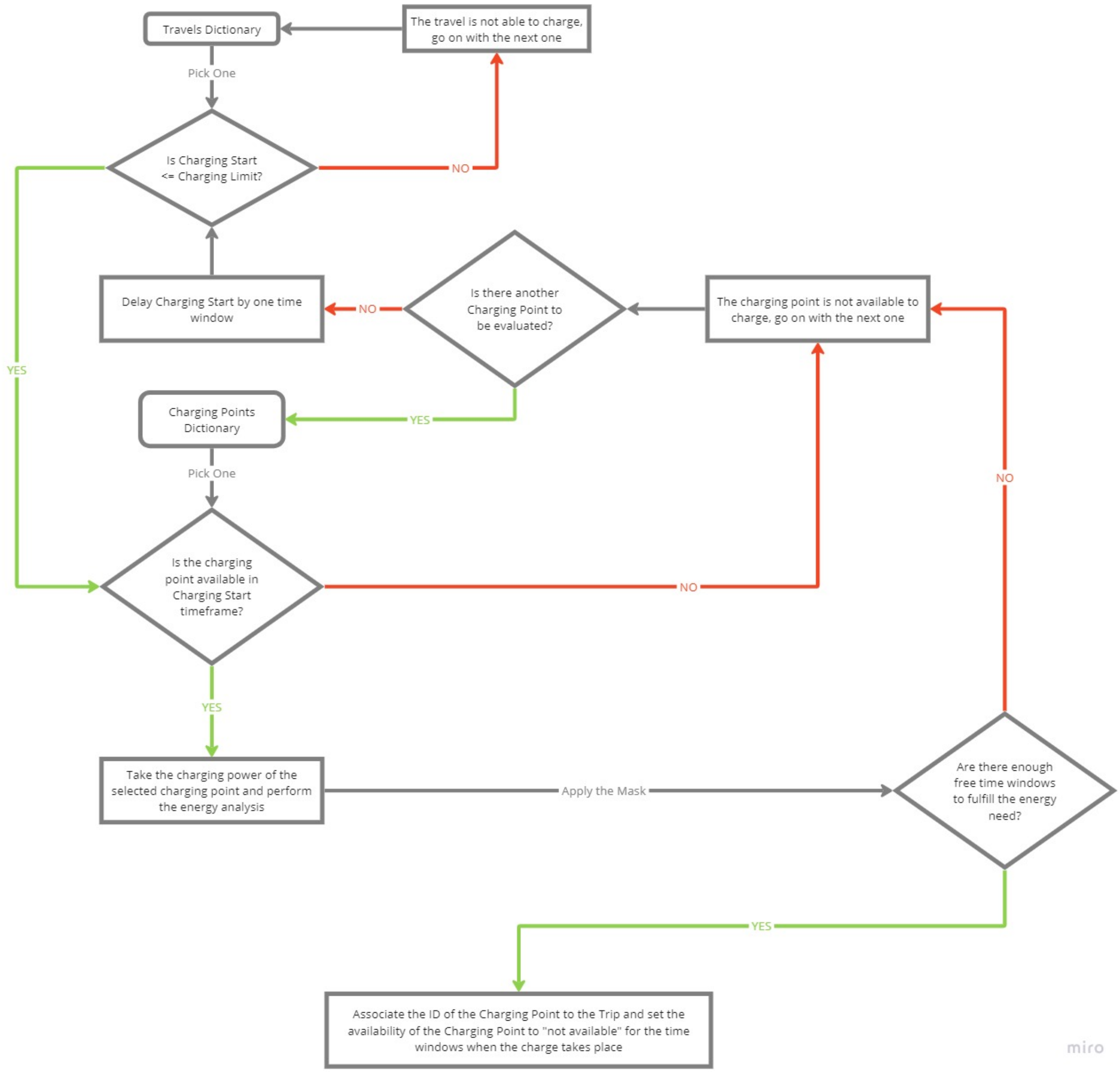


Figure 3.10: Energy analysis methodology for load profile creation

The outcome of the procedures described, applied respectively to *Return Home* and then *Work*, *Study* and *Leisure* trips allows to have for each travel that performs a charging process the **power list** variable that describes the charging session in terms of power and duration. Just by summing up these variables it is possible to have the value of the overall added load on the grid generated by the EV pool in the typical day modelled.

3.8. Frequency profile analysis

To test the potential offer in terms of frequency regulation related services of the EV pool under analysis, it is fundamental to preliminarily assess in detail frequency perturbations in a typical day. The input data consist in a record from the substation the university campus is associated with. The resolution of the input is one second so some processing is needed to make it coherent with the traffic simulation resolution of five minutes. The input file is sampled every five minutes and the maximum of the frequency distance from nominal value of 50 Hz is accounted to ensure the EV pool is able to support the grid in the most critical instant. Then the energy to be provided in the five minutes time window is computed as the integral of the power deviations required for grid support.

The first process to be performed is an analysis on whenever the grid is in need of primary frequency regulation. A power deviation is triggered whenever the frequency value deviates from the nominal value of 50 Hz by more than 20 mHz. If the deviation is positive, so the frequency is above 50.02 Hz the requirement is to reduce the power input while when the deviation is negative, so the frequency is below 49.98 Hz the demand is to increase the power input. It is crucial to notice that in this study the control logic is applied to an aggregate of electric vehicles operated with a smart charging logic (V1G) so comparable to a variable load. This requires a further reasoning on the presented logic: when requirement to traditional power plants is *"increase power input"* this is actuated by the pool by decreasing the withdrawal of energy so decreasing the charging power. Likewise, when the demand is *"decrease power input"* the action asked to the pool is to increase the power uptake.

To provide an analysis the more complete possible two different frequency profiles were took into consideration: the first one represents the average of the frequency oscillation measured in the considered substation during a whole year, the second is the *"worst day"* observed in the last year. With *"worst day"* it is indicated the day where the registered oscillations were the most severe.

In Figure 3.11 is represented the daily frequency profile averaged over a year of the Italian grid with highlighted thresholds outside of which it is required primary frequency regulation.

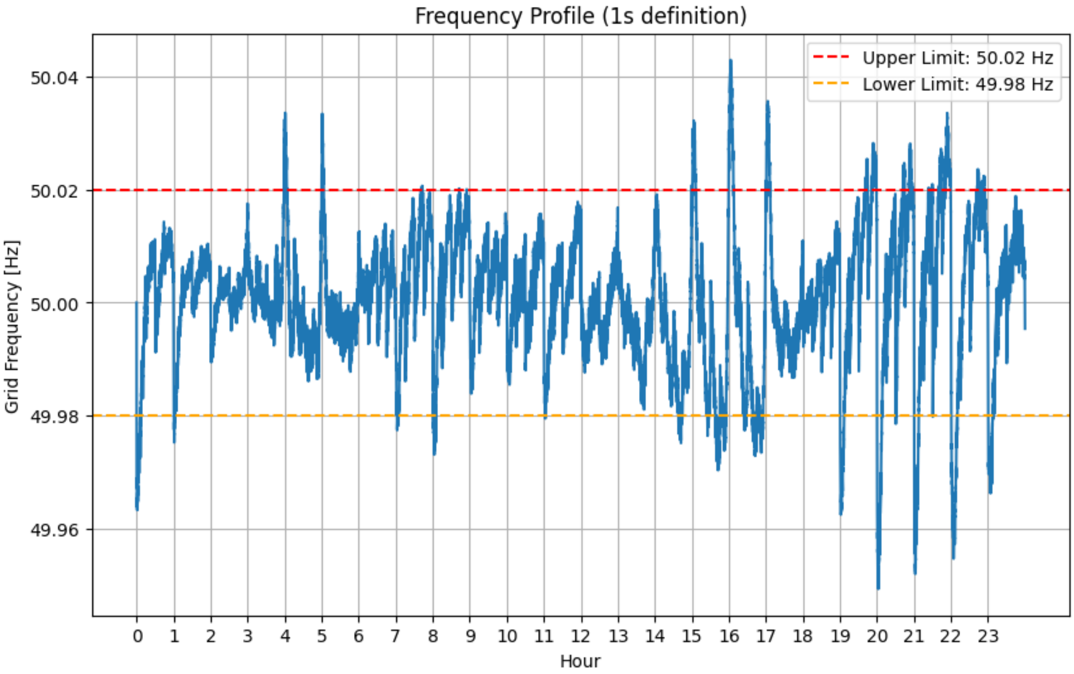


Figure 3.11: Daily grid frequency profile averaged

In Figure 3.12 instead is represented the daily frequency profile of the *"worst day"* observed with highlighted thresholds outside of which it is required primary frequency regulation.

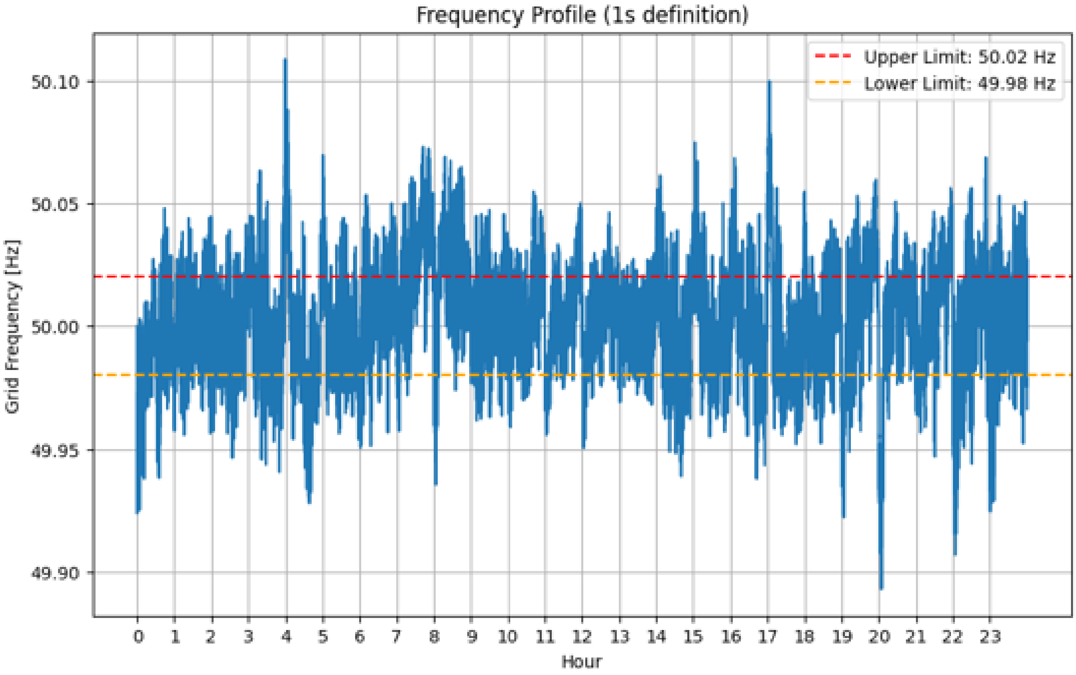


Figure 3.12: Daily grid frequency profile *"worst day"*

Having defined the input frequency profiles, it is essential to understand how the the response to frequency oscillations by selected units is structured. The increase or decrease of the power input is proportional to the frequency deviation according to the logic and the equations presented in the following. In Figure 3.13 it is reported a graphic description of the control method applied.

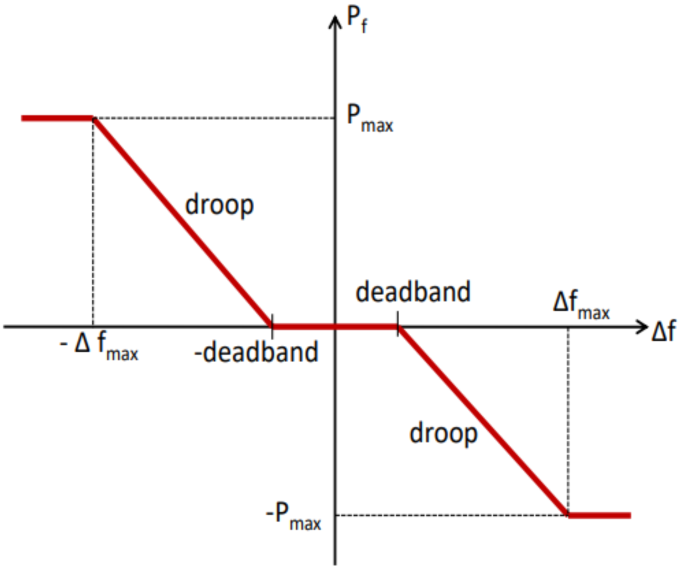


Figure 3.13: Required power modulation logic for primary frequency reserve

With *deadband* it is described the area of the frequency profile inside the threshold previously defined where no primary frequency control service is needed. With Δf *max* instead, it is defined the limiting value of frequency deviation from which on the required power modulation coincides with the maximum offered. The value of Δf *max* for Italian grid regulation is set to 57.5 mHz. In the frequency variation region between the *deadband* value and Δf *max* the power variation response follows a linear trend and its slope can be determined in the following two ways:

$$\sigma_p = -\frac{\frac{\Delta f}{50}}{\frac{\Delta P_e}{P_{eff}}} \tag{3.3}$$

$$K_r = -\frac{\Delta P_e}{\Delta f} = \frac{1}{\sigma_p} \cdot \frac{P_{eff}}{50} \tag{3.4}$$

In Equation 3.3 the parameter σ_p is called *droop* and it is a dimensionless quantity used to correlate linearly the frequency deviation and the power modulation. In Equation 3.4 instead, the slope K_r is directly computed. Applying the defined law to the frequency profile it is possible to assess the required increase or decrease in power at every instant once it is set a value for the maximum Power offered (ΔP_e). To determine this parameter it is necessary to run a dedicated analysis on the EV pool to find out the available *"flexibility band"* for every time window. With *"flexibility band"* it is meant the variation (increase or decrease) of charging power that each vehicle connected in the instant under analysis can withstand while respecting imposed constraints.

3.9. Flexibility bands evaluation

In order to contribute to primary regulation service a power plant must bid on the MSD market a quantity in power that is able to guarantee. In fact Terna could ask for contribution at any instant of the day and the plant called must be able to deliver the bid quantities, so as not to incur the expensive penalties provided for non-compliance with the established plan.

In order to evaluate the potential of the EV pool for frequency regulation it is essential to assess the available band the aggregate can offer in each time frame of the simulation. The first assumption to be made is whether the aggregator is the willing to offer flexibility only in one *"direction"* or in both. With *"direction"* it is meant:

- **Decrease Charge Direction**: the frequency of the grid is below the *deadband* threshold value, traditional power plants are called to inject extra energy, the aggregate (comparable to a variable load) is called to reduce the energy uptake.
- **Increase Charge Direction**: the frequency of the grid is above the *deadband* threshold value, traditional power plants are called to reduce injected energy, the aggregate (comparable to a variable load) is called to increase the energy uptake.

The EV pool is able to offer flexibility in *decrease charge* direction since with no active decision applied, to have a margin in decrease it is sufficient to decrease by a fixed percentage the charging power of vehicles under a charging session in a determined time window. Conversely for *increase charge* direction it is necessary to limit charging columns to a given percentage of their nominal power output in advance to "create" a potential bandwidth. This clearly lengthens the charging time of the whole pool. For this study the maximum percentage of reduction/increase of charging power of the single charging point is set to 10% in order to limit the impact on charging time and not to excessively stress power electronics and EV batteries.

Once it is established in which direction the aggregator is going to offer flexibility it is necessary to know the effective amount of power that can be provided per each time frame of the simulated day. In this process the fundamental constraint at the base of all the logic implemented must be kept closely controlled: energy delivered to the final user must not be impacted by the participation to any grid service. Starting from this assumption in any time window it is possible to evaluate the number of connected vehicles that can offer flexibility. To be considered *"available"* the EV considered must be able to fulfill its charging needs even if called to change its charging power to offer flexibility. In Algorithm 3.3 and Algorithm 3.4 the two processes to evaluate the number of available vehicles and the related band in each time window are presented.

Algorithm 3.3 Band Evaluation for Primary Frequency Regulation "Decreasing Charge"

```
for time frame in daily simulation do
    for travel in charging travels do
        Apply the mask defined in section 3.7 and Figure 3.9 to find if the selected vehicle is charging in the selected time frame
        if the travel is charging and its type is Return Home then
            if there is time to make up for missing energy then
                The travel is counted as available and its contribution to the band is 10% of the associated charging power
            end if
        else if the travel is charging and its type is not Return Home then
            if there is enough time to make up for missing energy and charging point is available then
                The trip is counted as available and its contribution to the band is 10% of the associated charging power
            end if
        end if
    end for
end for
```

Algorithm 3.4 Band Evaluation for Primary Frequency Regulation "Increasing Charge"

```
for time frame in daily simulation do
    for travel in charging travels do
        Apply the mask defined in section 3.7 and Figure 3.9 to find if the selected vehicle is charging in the selected time frame
        if the travel is charging and is not at the end of the charging process then
            The trip is counted as available and its contribution to the band is 10% of the associated charging power
        end if
    end for
end for
```

From the described algorithms it is clear how the case of a request in *"decrease charge"* direction is much more critical from the point of view of the aggregate because extra time windows are needed to satisfy the energy requirement. This constraint particularly impacts the number of *"available"* vehicles during the hours of peak request of public charging because if the charging point is already booked for another charging session immediately after the end of the current process, the vehicle charging is not considered *"available"* since its participation to flexibility provision would not be compatible with mobility service for the next user, that has the absolute priority.

3.10. Bands enhancement

To have a significant impact on grid stability it is crucial to offer a band as uniform as possible throughout the day. To aim at this goal, the proposed methodology implements a *"load shifting"* strategy to enhance the band available for the aggregator that can be bid on the market. The focus is clearly on how to enlarge the number of available vehicles for the offer of flexibility services in the most critical hours of the day.

The underlying idea to achieve the presented objective is to postpone charging sessions that start in time windows when the load profile is above its average trying to fill the valleys to achieve a load profile as uniform as possible. Clearly each time a modification to the charging start of a travel is implemented, several constraints need to be checked depending on the typology of travel is being processed. *Return Home* travels due to their definition have no restrictions related to the availability of their charging spot while for the other typologies there is the need to check if a reservation for the related charging point in the time windows immediately after the end of the charging process is present.

The flexibility is given by the *"Extra time"* described in Figure 3.14, together with the constraints on charging point availability if the travel type is not *Return Home*.

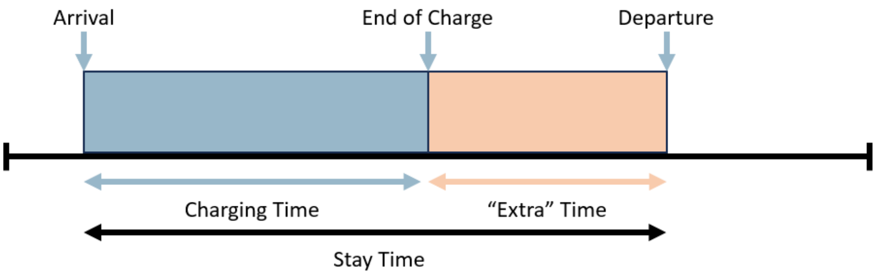


Figure 3.14: Staytime description

Algorithm 3.5 Primary Band Optimization

```
for iteration number in range do
    Find and select all time windows when the load profile is above its average
    for time window in selected time windows do
        for travel in charging travels do
            if travel charging start is in selected time windows then
                Check if the travel is able to fulfill its energy need even starting its charging process one time window later (charging end does not coincide with charging limit)
                If so, move charging start ahead of one time window and update consequently charging end and power list attributes
            else if the travel is charging and its type is not Return Home then
                Check if the travel is able to fulfill its energy need even starting its charging process one time window later (charging end does not coincide with charging limit and there is at least one free time frame after charging end in the availability list of the associated charging point)
                If so, move charging start ahead of one time window and update consequently travel charging end and power list attributes and availability list in the related charging point variable
            end if
        end for
    end for
end for
```

The procedure described in Algorithm 3.5 allows to postpone travels that finish their charging process a lot earlier than their *Charging Limit* in order to smooth peaks of the load profile and increase its valleys. This way the number of travels charging in each time window of the simulation is much more uniform and consequently also the primary frequency regulation band that can be offered.

3.11. Primary regulation service

Once the available band for primary frequency regulation is determined, as described in the previous section, its value is used as the P_{max} value necessary in Equation 3.4 reported in section 3.8. This way the peak of frequency deviation is associated to a maximum reduction/increase in power uptake by the EV pool equivalent to the minimum of the daily available band, ensuring the service can be delivered to the grid in any time frame of the day it is needed.

It is now possible to apply the changes resulting from calls to offer flexibility to the single charging processes to show the actual impact that the provision of this service has on the EV pool. The proposed approach divides the required power deviation among all vehicles marked as *"available"*, in order to minimise the burden on single charging processes. This way the higher the number of *"available"* vehicles, the lower will be the required power deviation to each vehicle at equal need from the grid. In Algorithm 3.6 the key operations performed to achieve this objective are reported.

Algorithm 3.6 Implementation of Primary Regulation Service

```
if service in ”decrease” or ”both”directions then
    for time window in calls for decrease charge do
        Compute the contribution from each single vehicle dividing the required power reduction by the number of "available" vehicles computed in Algorithm 3.3.
        for travel in charging travels do
            if the travel is charging and its type is Return Home then
                Subtract from travel's power list" variable the value of the computed contribution in the position of the selected time frame
                Add the missing value to the first time window after the previous end of the charging process
                Update all the modified variables
            else if the travel is charging and its type is not Return Home then
                Same behaviour as the one described for the "Return Home" travels but also the availability variable of the corresponding charging point needs to be updated
            end if
        end for
    end for
else if service in ”both”directions then
    for time window in calls for increase charge do
        Compute the contribution from each single vehicle dividing the required power reduction by the number of "available" vehicles computed in Algorithm 3.4.
        for travel in charging travels do
            Add to travel's power list variable the value of the computed contribution in the position of the selected time frame
            Subtract the extra energy value from the next time window of the charging process
            Update then all the modified variables
        end for
    end for
end if
```

3.12. Tertiary reserve

3.12.1. Tertiary reserve bands evaluation

As mentioned in section 2.6 tertiary reserve is a crucial service the TSO requires to restore the margin of adjustment necessary to ensure the stability of the grid. In Italy Terna allows each qualified unit to participate in the market offering couples energy-price for each hour of the ones between each session of MSD (see Figure 2.6 in section 2.5 to see details on time span of each MSD session). The energy bid on the market is correspondent to a reduction or increase in the power output of the plant. In the case of the study, if the EV aggregate is selected to provide tertiary reserve in a certain hour, the energy uptake must be reduced or increased of a certain value and the new set point reached must be kept for the whole hour duration. The longer time scale of the required variations for this service makes more challenging to respect the constraints regarding full charge of single vehicles. In Algorithm 3.7 and Algorithm 3.8 the two processes to evaluate the available bands for the offer of tertiary reserve in each hour of the day are presented.

Algorithm 3.7 Band Evaluation for Tertiary Frequency Regulation "Increasing Charge"

```
for hour in daily simulation do
    for travel in charging travels do
        Apply the mask defined in section 3.7 and Figure 3.9 to find if the selected vehicle is charging in the selected hour
        if the travel is charging then
            Count how many time frames of the charging process of the selected travel falls under the selected hour
            Count how many time frames between the last one of the selected hour and the charging end of the selected travel are available to compensate the extra energy injected in common window
            The available band for the vehicle will be the minimum between the 10% of the associated charging power and the energy that can be not charged in time frames between the last one of the selected hour and charging end, spread on common time frames
        end if
    end for
end for
```

Algorithm 3.8 Band Evaluation for Tertiary Frequency Regulation "Decreasing Charge"

```
for hour in daily simulation do
    for travel in charging travels do
        Apply the mask defined in section 3.7 and Figure 3.9 to find if the selected vehicle is charging in the selected hour
        if the travel is charging and its type is Return Home then
            Count how many time frames of the charging process of the selected travel falls under the selected hour
            Count how many time frames between charging end and charging limit of the selected travel are available to make up for the charge reduction in common windows
            The available band for the vehicle will be the minimum between the 10% of the associated charging power and the energy that can be charged in time frames between charging end and charging limit spread on common time frames
        else if the travel is charging and its type is not Return Home then
            Count how many time frames of the charging process of the selected travel falls under the selected hour
            Count how many free time frames between charging end of the selected travel and the next charging session start in the associated charging point are available to make up for the charge reduction in common windows
            The available band for the vehicle will be the minimum between the 10% of the associated charging power and the energy that can be charged in free time frames after charging end spread on common time frames
        end if
    end for
end for
```

It can be noted how for the band in *"increase charge"* direction there is no difference among the different typologies of travels since the limit is represented by the capacity of the battery. This means there must be a sufficient number of time windows between the end of the service request and the end of the charging process when the charge power can be reduced to respect the constraint presented by the capacity.

3.12.2. Tertiary reserve acceptance model

To properly study the impact of an aggregate like the one modelled on the flexibility provision by the TSO it is crucial to understand and model how often the grid is in need of this kind of service and how Terna selects which plants are called to fulfill the manifested need.

Starting from a database on calls for tertiary reserve provision by Terna in past years it is observed that the average acceptance for offers in the balancing market by Terna is around 5.5%. This particularly low value is coherent with current low competitiveness of renewable and distributed energy sources highlighted in [44] and [45].

The obtained probability needs to be concatenated with other two key parameters that are noticed to strongly influence the probability of being called to provide this service: price and offered power. Tables for each hour reporting a probability corresponding to a couple price-power are built for both offers in *increase* and *decrease* directions. The result is a collection of 24 tables for each direction describing the probabilities of being accepted in each hour of the day.

Probability of being accepted in "decrease" direction					
"Hour 1"	Power Offered [MW]				
Price (% of Market Price)	1	5	10	...	1000
0	0	0	0	...	0
0.01	6.15	6.47	6.62	...	11.10
...	...	...	...	...	...
0.9	42.23	43.64	43.88	...	92.94

Table 3.7: Acceptance probabilities as function of power and price deviation

Probability of being accepted in "increase" direction					
"Hour 1"	Power Offered [MW]				
Price (% of Market Price)	1	5	10	...	1000
1	49.88	50.09	50.27	...	97.96
1.01	49.69	49.90	50.08	...	97.77
...	...	...	...	...	...
1.9	21.76	21.79	21.82	...	30.41

Table 3.8: Acceptance probabilities as function of power and price deviation

The created data set is then integrated in the simulation following the procedure described in Algorithm 3.9.

Algorithm 3.9 Acceptance Probability Evaluation for Tertiary Reserve Provision

```
for day in a year do
    for hour in daily simulation do
        if the flexibility offer is only in "decrease" direction then
            Give as input the minimum of the available tertiary band in "Decrease Charge" direction computed as described in subsection 3.12.1 in the selected hour and the desired deviation from market price
            Enter the table relative to the selected hour, linearly interpolate between the two closest power values if needed and obtain as an output the probability of being accepted
        else if the flexibility offer is in "both" directions then
            Apply in addition to the procedure described for "Return Home" travels another analogous one giving in input the band and the table relative to "Increase Charge" direction
        end if
    end for
end for
```

The output of the explained algorithm is a list of 8760 elements (equal to the number of hours in a year) where in each position the probability of being called by the TSO to offer tertiary reserve is stored. Since the simulation regarding the traffic model and the load profile evaluation is performed for a typical day the probabilities in the output list are repeated every 24 hours.

Applying a random selection process based on the probabilities contained in the output vector it is possible to simulate when and how often the TSO calls the aggregate to provide tertiary reserve. The final result is then a binary array where the latter indicates the hours when the EV pool is required to change its set point to support the grid.

3.12.3. Tertiary reserve service evaluation

The output of the analysis just described in subsection 3.12.2 is then a record with all the calls from the TSO to the modelled aggregate for offering tertiary reserve. The next step in the simulation is to actually implement the requests to the EV pool to evaluate the impact on the shape of the load profile.

To satisfy the request from the TSO the aggregate needs to generate a deviation from the setpoint equal in power and direction terms to the value bid in balancing market and keep this new condition for the whole hour in which it is called to provide the service.

To minimise the impact on the single EV user the overall required deviation is spread among all the "available" vehicles. In Algorithm 3.10 and Algorithm 3.11 are reported the implemented logic to apply the tertiary reserve service to the EV pool in *"Decrease Charge"* and *"Increase Charge"* direction respectively:

Algorithm 3.10 Implementation of Tertiary Reserve Service

```
for hour in selected hours for tertiary service do
    for 5 minutes time window in selected hour do
        Compute a reduction factor equal to the band bid in the balancing market (equal to the minimum value at disposal in the hour under evaluation) and the available band in the selected time window
    end for
    for travel in charging travels do
        if the travel is charging and its type is Return Home then
            Evaluate the common time windows between the charging process of the selected travel and the hour under evaluation
            Subtract in selected positions of travel's power list the value of the available band relative to the specific travel computed in the previous paragraph multiplied by the just obtained reduction factor
            Compute how many time frames between charging end and charging limit of the selected travel are available to make up for the charge reduction in common windows
            Spread uniformly among them the energy missing due to the reduction applied
        else if the travel is charging and its type is not Return Home then
            Same behaviour as the one described for the "Return Home" travels but as free time frames are considered the ones between charging end of the selected travel and the next charging session start in the associated charging point
            Update, additionally to the power list attribute of travels dictionary, also the availability attribute in the charging points dictionary related to the considered charging spot accordingly to the performed modification
        end if
    end for
end for
```

Algorithm 3.11 Implementation of Tertiary Reserve Service

```
for hour in selected hours for tertiary service do
    for 5 minutes time window in selected hour do
        Compute a reduction factor equal to the band bid in the balancing market (equal to the minimum value at disposal in the hour in question) and the available band in the selected time window
    end for
    for travel in charging travels do
        if the travel is charging and its type is Return Home then
            Evaluate the common time windows between the charging process of the selected travel and the hour under evaluation, add in selected positions of travel's power list the value of the available band relative to the specific travel computed in the previous paragraph multiplied by the just obtained reduction factor
            Compute how many time frames between charging end and charging limit of the selected travel are available to reduce charging power and compensate extra energy withdrawn in common windows
            Spread uniformly among them the added load by dividing the excess energy by the number of time frames out of the request
        end if
    end for
end for
```

As clearly stated in the presented algorithms, the constraint about fulfilling completely the energy request by each user is strictly respected. The consequence on the load profile is that whenever the aggregate is being called to provide a flexibility service to the TSO (both in increase or decrease) the deviation from the declared set point demanded causes a subsequent deviation in the opposite direction to compensate the disequilibrium generated. This behaviour, on the one hand is necessary to provide full service to the users, on the other hand generates undesired deviations from the set point that could potentially harm the stability of the grid. This aspect is carefully analysed in the following sections and two approaches are adopted: the first is a quantification of the impact of the generated unwanted deviation on the revenues generated by the aggregate, the second is the creation of a parallel model where the constraint on fulfillment of energy requests is relaxed to avoid any drift from set point.

3.12.4. Zonal unbalances economic evaluation

As described in section 2.9, the TSO applies penalties in case of an unbalance generated by the connected unit with respect to the declared plan. From Table 2.4 and Table 2.5 it is clear how the *"dual pricing algorithm"* is more penalizing for units that produce an imbalance, since if the imbalance has opposite sign than the zonal one, no penalty is applied while in the *"single pricing algorithm"* if the signs of the unbalances are opposite the unbalanced unit can even benefit from its imbalance if the average price in the MSD is cheaper than the one previously granted in the MGP.

Having set the framework for the correspondence of a monetary value to an unbalance it is possible to assess the economical impact of the unwanted unbalances on the revenues from grid services the aggregate can generate. To do so a yearly record of zonal unbalances related to northern Italy zone is taken as an input, it is then combined with MSD and MGP market price values to be able to properly apply the previously presented logic. To quantitatively estimate the values in terms of energy of the unbalances of the aggregate a simulation over a year is run following the scheme presented in Algorithm 3.12:

Algorithm 3.12 Unbalances value estimation

```
for day in a year do
    Extract data on zonal sign, MSD price and MGP price relative to the selected day.
    Take from the output of the analysis on acceptance described in subsection 3.12.2 the hours indices of the selected day when the aggregate is called to provide tertiary reserve
    Apply the algorithm for tertiary service impact evaluation on the profile presented in subsection 3.12.3 and compute the unwanted unbalances as the difference between the actual load profile and the set point (clearly excluding detour required for tertiary reserve service)
    Combine the information on values and sign of the unbalance of the aggregate with the sign of zonal unbalance and the price value to quantify the economic implications following instructions presented in Table 2.5 or Table 2.4
end for
```

3.12.5. Partial charging simulation

The second approach to tackle the problematic of unwanted unbalances after the provision of Tertiary Reserve is to relax the constraint on the fulfillment of the energy request of each single travel. This way, are the vehicles that absorb deviations from the set point, changing the amount of energy drawn during the charging process. In the new parallel model a number of adjustments are applied to the codes in order to adapt some of the key computations to this new approach.

To assess the potential of the aggregate it is crucial to set reasonable boundaries for the deviations from required energy, so as to determine which vehicles can provide flexibility with limited impact on their charging demand. As reasonable values for these parameters in the presented simulation it is taken 80% of the request as a lower limit, meaning at least 80% of the energy request by each vehicle must be satisfied regardless of the provision of services to the grid. As an upper limit instead was chosen 10% of requested energy that can be charged on top of the initially required one. This assumption imply that the battery of the vehicles has still a spare capacity equal to the 10% of the energy requested in the last charging process performed.

In the following list the main changes applied to the codes presented during the description of the methodology are summarised:

1. **Primary bands evaluation**: (Modifications to Algorithm 3.3 and Algorithm 3.4)

   To count for *"available"* vehicles it is no more needed to evaluate the presence of free time windows after the end of the charging process (for band in *"Decrease Charge"* direction) or of other time windows in the charging process after the call for providing the service (for band in *"Increase Charge"* direction). Instead it is required to check the impact of a reduction or increase in charging power related to a call to offer primary frequency regulation and verify if it is inside the limits previously presented.

2. **Primary regulation service**: (Modifications to Algorithm 3.6)

   Once new bands are evaluated the process is analogue to the one of the original simulation: the band to be offered is divided among all the available vehicles to minimize the impact on each charging process. The difference is that, this time, the missing or extra energy is not compensated. The found values are just subtracted or added from **power list** attribute of each travel. A new variable to account the percentage of completion of required recharge is created and updated.

3. **Tertiary bands evaluation**: (Modifications to Algorithm 3.8 and Algorithm 3.7)

   As for primary bands evaluation the contribution from available vehicles is computed from the missing or extra energy each vehicle can withstand without going outside the imposed limits. As it happened with the original model, since tertiary reserve must be offered for a whole hour the bandwidth that can be offered suffers more from the constraints imposed.

4. **Tertiary Reserve Service**: (Modifications to Algorithm 3.11 and Algorithm 3.10)

   Here the code is simplified with respect to the original one since no compensation for missing or extra energy needs to be accounted. The computed band value for each vehicle is subtracted or added to the charging power values in **power list** variable in time windows when the aggregate is providing tertiary reserve. The associated variable that accounts for percentage of completion of required recharge is updated.

3.13. General parameters description

The model described in the previous chapter can be used to analyse different scenarios by setting and tuning different parameters. In the following are reported all the possible options that can be adopted by the model.

- EV penetration rate: value in %
- Number of public charging points: free-choice integer number for the user
- Power of public charging points: list of values describing different nominal power output in kW
- Power share of public charging points: list of values containing probabilities to have a charging point with the correspondent power output
- Power modulation percentage: value in %
- Charging process efficiency: value with the assumed efficiency of a charging process
- Primary regulation service: variable that can be set to 'down' if flexibility is offered only in 'decrease charge' direction (charging power is the nominal one of chargers), or to 'both' if flexibility is offered in both directions (to create a margin for 'increase charge' direction charging power is preliminary set to 90% of the nominal one)
- Maximize primary band: if set to 'yes' the code applies to the EV pool the band maximization algorithm, if set to 'no' it does not

- Frequency profile: variable to choose the input frequency profile between the *"average"* and the *"worst day"* profiles
- Modulation margin: value that sets a constraint on the maximum fraction of nominal power of the charging points that can be decreased/increased for the offer of flexibility services
- Tertiary reserve service: if set to 'yes' the code performs all the computations needed for the evaluation of Tertiary Reserve Service potential from the EV pool, if set to 'no' it does not
- Price decrease: factor between 1 and 4 that represents the deviation from MGP price that is offered for the provision of tertiary reserve in *"Decrease Charge"* direction
- Price increase: factor between 0 and 1 that represents the deviation from MGP price that is offered for the provision of tertiary reserve in *"Increase Charge"* direction

Having now clear which are the possible options for the setting of the simulation in the following are presented firstly some of the parameters that will be kept constant along the reported results. In the simulation 2.5% of EV penetration is considered. The current value of EV penetration in Lombardy is below 1% but considering the growth in the adoption of this technology the scenario is meant to depict the situation in few years.

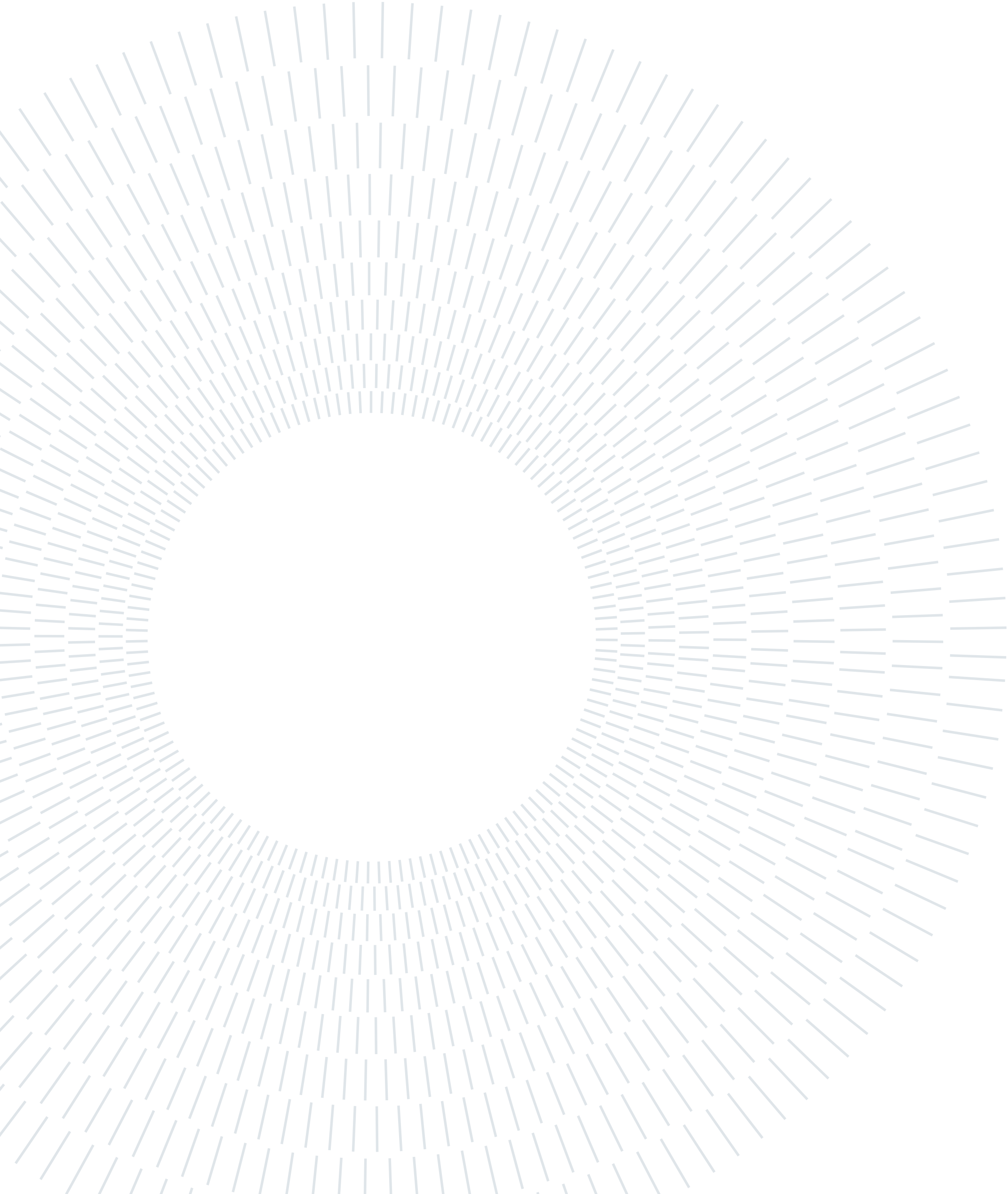
The implication of this assumption is that out of the overall number of travels, 2.5% are performed by EVs. Out of an initial pool of 7882984 daily travels in Lombardy from the input OD matrix described in section 3.3, 197075 are selected to be *"electric"* travels. The overall number of charging points is set to 15000, a number in line with the growth scenario set for the electric vehicles penetration. Currently the number of public charging points in Lombardy is around 7500 [46], so the assumption is that following the growing adoption of electric vehicles also public charging infrastructure is going to grow almost proportionally, doubling in a few years the number of charging spots available.

Regarding the nominal power output of charging spots the values chose in the simulation are 6 kW and 22 kW. As stated in section 3.6 in the evaluation of flexibility services it is not reasonable to include high power stations, designed for fast charging processes, not compatible with a modulation logic. The share among the two chosen values is defined as 20% probability of having a 22 kW charging spot, 80% probability of having a 6 kW one, in line with the current share of power stations deployed in the territory. Regarding domestic charging spots instead, they are assumed to be all at 6 kW, since wall-boxes currently on the market typically present a nominal power close the the chosen one.

Another crucial parameter is the maximum allowed power deviation percentage. Its value is set to 10% in order to have a limited impact on charging time and reduce the stress on power electronics and EV's batteries. In case of flexibility offered only in *"decrease charge"* direction, the power of the charging spot can span from the nominal one to 90%. When evaluating the both directions cases, the power spans from the nominal one to 80% of it, since preventively set to 90% of the nominal.

Parameter	Electric travels	Public chargers	Domestic chargers
Number	2.5%	15000	n.d.
Power	n.d.	20% at 22 kW, 80% at 6 kW	6 kW

Table 3.9: Main parameters setting



4 | Results and discussion

4.1. Charging habits preliminary analysis

To better understand the charging processes responsible of the added load on the grid a first analysis on when charging processes are starting most frequently (Figure 4.1) and how long charging times are (Figure 4.2) is run.

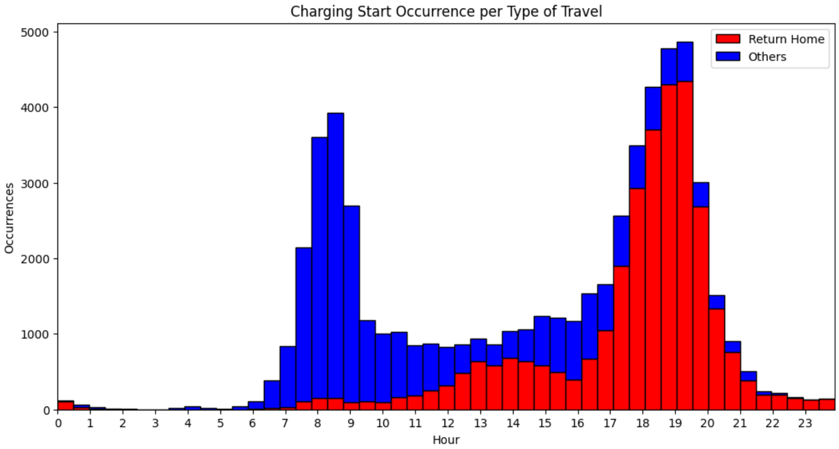


Figure 4.1: Charging Start Occurrences for Different Travel Types

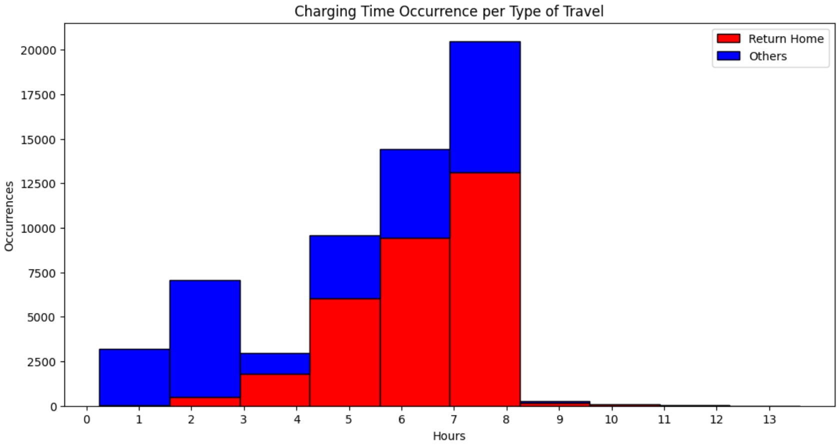


Figure 4.2: Charging Times Occurrences for Different Travel Types

As it is evident from reported histograms most of *"Return Home"* travels start charging between 6 p.m. and 7 p.m. and takes between 6 and 8 hours to finalise their charging process. The consequence is that from 3 a.m. to 8 a.m. (hour when a consistent number of travels starts charging) there is a very limited number of charging processes ongoing. This results in the inability to offer flexibility services during the hours mentioned, as it will be better detailed in the upcoming analysis.

4.2. Different scenarios presentation

To properly present how the different settings impact on the results of the model different simulations will be presented in the following, each one with a unique setting.

Firstly it is essential to separate the two different logic dealing with unbalances as respect of energy requests. The results from simulations where the constraint on fully satisfy the energy request from EVs is present, and consequently unbalances are generated, are addressed with *"full charge"* in the following subsections. Simulations where the process applied is the one described in subsection 3.12.5 instead are reported with the caption *"impacted charge"*.

Then the case when the EV pool offers flexibility only in *"decrease charge"* is distinguished from the case when the offer is in both directions. The former is indicated with the *"only decrease"* caption and refers to a scenario where chargers are operated at nominal power and modulation can be operated only by decreasing power uptake. The latter is pointed as *"both directions"* and refers to simulations where the charging points are operated at 90% of the nominal power, having so the possibility to be modulated in both directions.

In the end it is needed to differentiate the simulations where the *"bands enhancement"* algorithm presented in section 3.10 is applied to the aggregate or not.

Given this overview, the possible options are eight:

Simulation Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Charge Logic	Full Charge				Impacted Charge			
Directions	Both	Down	Both	Down	Both	Down	Both	Down
Bands Enhancement	No	No	Yes	Yes	No	No	Yes	Yes

Table 4.1: Presented simulations summary

4.3. Simulation 1

Having at disposal for each travel asking for charge its power request in every time window (described by the **power list** variable), it is possible to build the added load profile due to charging processes by simply summing up all the **power lists**. This way the extra load from charging processes will have the form of a list type variable as its components, with a granularity of five minutes.

In Figure 4.3 is depicted the total added load profile resulting from charging processes of all EV asking for charge in Lombardy region under the defined assumptions. With blue color is highlighted the contribution from charging processes taking place at public charging stations while in green it is shown the load from domestic charging sessions.

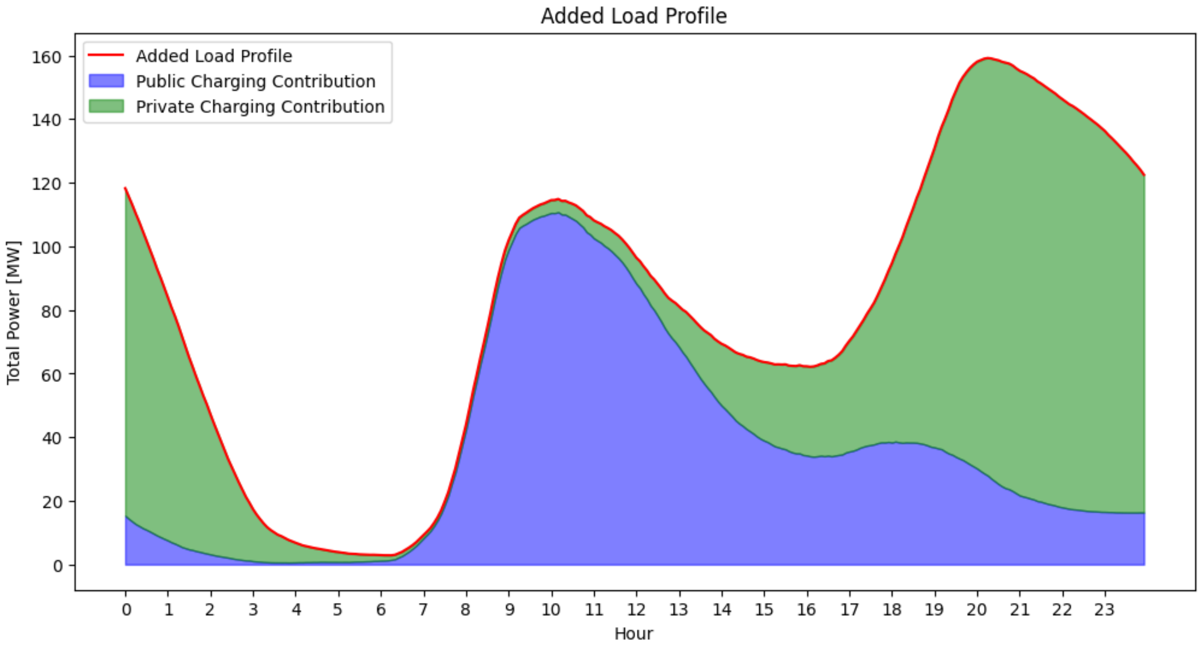


Figure 4.3: Added load profile with contributions from public and domestic charging

The profile shows two peaks: one in the morning between 9 a.m. and 12 a.m. that is mostly attributable to morning travels for work reasons that start charging once reached the workplace. The second is located around 8 p.m. and is instead relative mostly to *Return Home* trips that exploit domestic charging to fulfill their energy needs.

The peak in the evening reaches a higher value with respect to the one in the morning and the reason of this behaviour can be explained by two main factors. The first is that, since the simulation refers to a typical day and models travels inside Lombardy region (travels that starts or ends outside the region's boundary are excluded by the traffic model analysis), the number of return home travels performed by EVs must be the same as the sum of the other typologies of travels. So 50% of the overall travels are *return home* that are concentrated in evening hours and are responsible for the evening peak while the other typologies present more various occurrences throughout the day. The other reason is that most of the travels that charge during the day performs the charging process at a public charging station. So in spite of having an higher average charging power (20% of public charging points have a charging power of 22kW), the peak is influenced by the availability of charging spots.

To appreciate this second effect in Figure 4.4 it is represented the added load relative only to charging processes taking place at public charging spots.

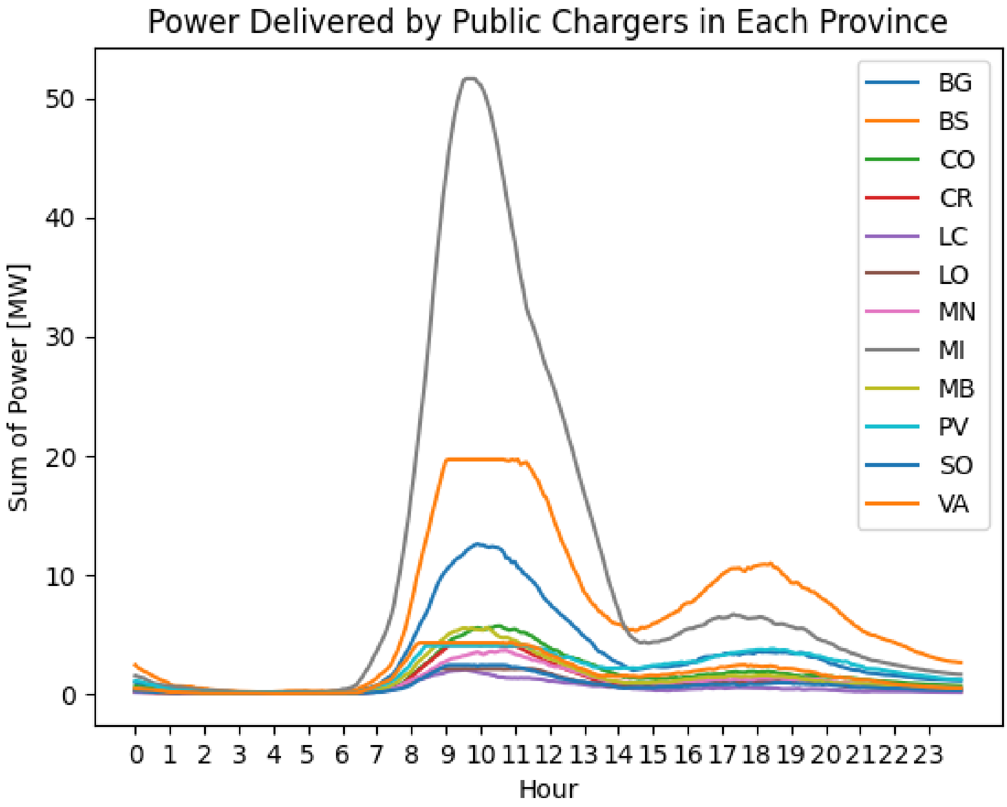


Figure 4.4: Total added load due to charging processes in public charging spots per province

Taking as an example what happens in the province of *Brescia (BS)*, the added load value reached from around nine a.m. and maintained until twelve a.m. is indicating that the public charging points in the province are all busy because charging processes are undergoing in each of them. The number of available public charging points in each province is reported in Figure 4.5 and confirms the behaviour just described.

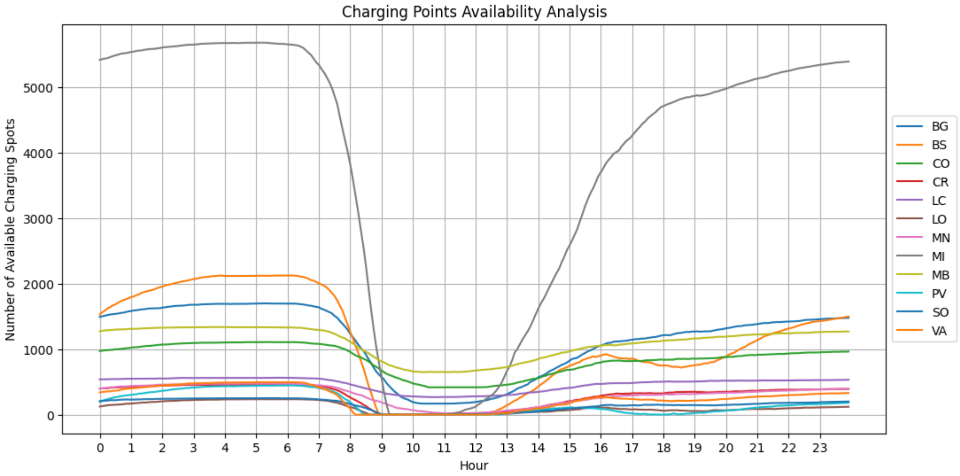


Figure 4.5: Number of available public charging points in each province

Having the geospatial information on where trips arrive, it is possible to assess under which primary substation their charging process will take place and so determine the added load per each substation at every hour of the day. In Figure 4.6 it is displayed Lombardy region divided into its primary substations areas colored in function of the added load generated by charging processes at 5a.m., at 10 a.m. and at 8 p.m. respectively.

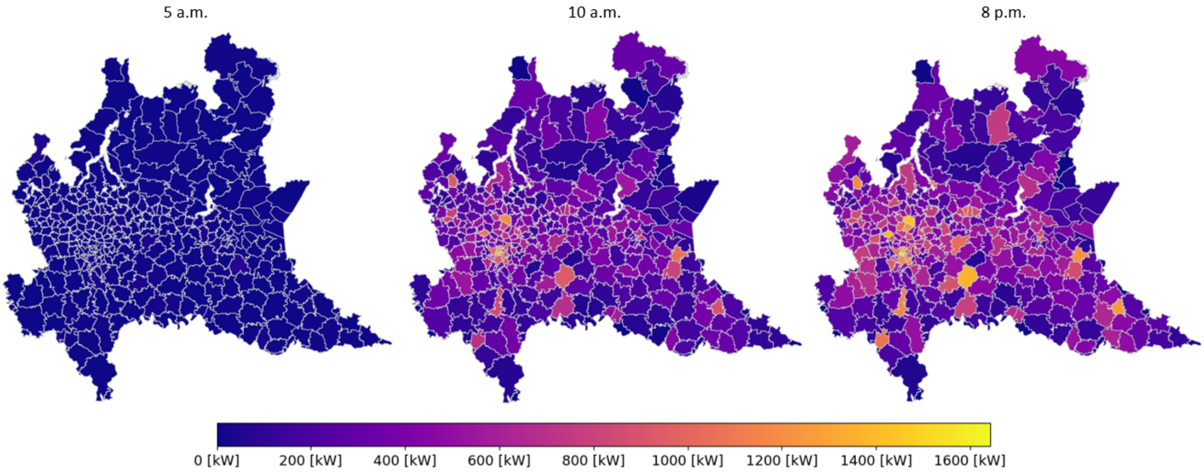


Figure 4.6: Added load from charging processes spatial distribution

After having determined the load profile generated by charging processes to evaluate the potentiality of the EV pool for the contribution to primary frequency regulation it is necessary at first to analyse the frequency profile and then to determine the available regulation band the aggregate can offer.

The output of the frequency profile analysis presented in section 3.8, consists in two different variables containing for all the seconds in the analysed day when primary frequency regulation is required and the correspondent power variation values computed through Equation 3.4. In Table 4.2 and Table 4.3 as an example of the output, are reported required power variations values from a simulation performed setting to 12 MW the value for the maximum power offered (ΔP_e).

Power to be decreased							
Second of the day	8	9	10	...	100	101	102
Power to be decreased [MW]	-1.6	-2.1	-2.4	...	-4	-4.2	-4

Table 4.2: Example of required decrease in power for primary frequency regulation

Power to be increased						
Second of the day	14330	14331	14332	...	14422	14423
Power to be increased [MW]	0.3	0.3	0.4	...	1.1	0.8

Table 4.3: Example of required increase in power for primary frequency regulation

The following step in the simulation is to establish the available regulation bands for primary regulation service that can be provided by the aggregate, as described in section 3.9. The result of the procedure is reported in Figure 4.7, where the available bands in both (*"decrease charge"* and *"increase charge"*) directions are depicted.

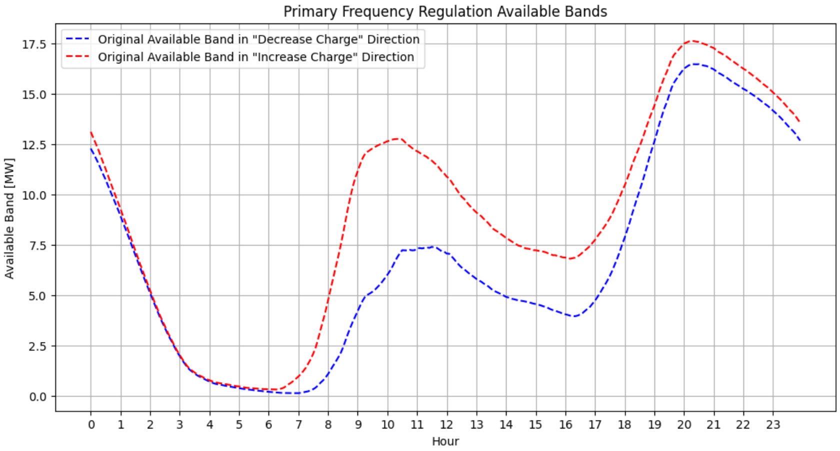


Figure 4.7: Primary frequency regulation available bands

The additional restrictions imposed by the necessity of free time windows at the end to the charging process to satisfy the energy need in case of a *"decrease charge"* request are particularly evident in the hours from 7 a.m. to 17 p.m.. The high request of charging sessions in pubic charging points means that there are very few free time windows between different charging processes at any single charger, and this significantly reduces the number of vehicles considered "available".

Once the value of the available band is set it is possible to establish for each MSD session the power deviation the aggregate can bid, computed as the minimum of the two bands in the four-hours time window of the market session. This value is used than as ΔP_e in Equation 3.4 to determine the response of the EV pool to the frequency profile deviations. The result of this process is shown in Figure 4.8 where especially for evening hours (when band value is consistent), it is evident the deviation from the set point to compensate for frequency oscillations of the input frequency profile that is reported once again in Figure 4.9 to better appreciate the call-response behaviour modelled.

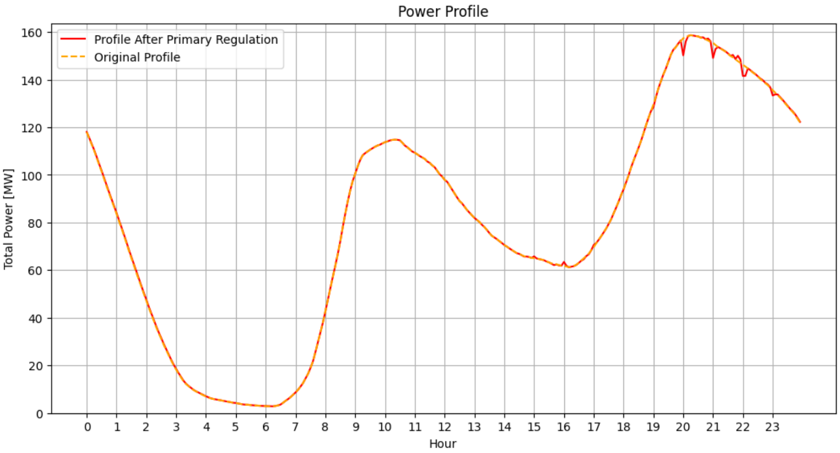


Figure 4.8: Load profile before and after primary frequency regulation provision

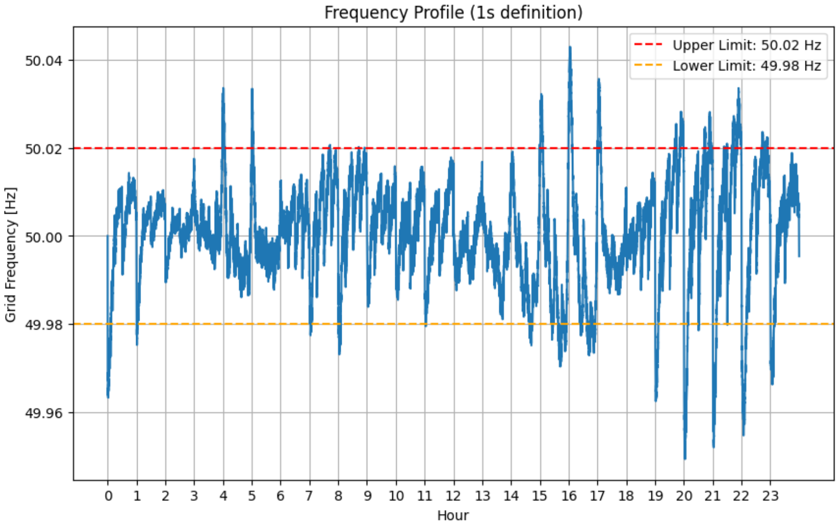


Figure 4.9: Daily grid frequency profile averaged

Then the contribution to tertiary reserve from the aggregate is investigated. As done for primary regulation service it is necessary to assess the available bands (subsection 3.12.1), find a criteria to determine whether the pool is called or not by the TSO to provide the service (subsection 3.12.2) and evaluate the impact of the service provision on the charging processes and consequently on the added load profile (subsection 3.12.3). The result of bands evaluation is reported in Figure 4.10 and shows the same behaviour of bands for primary frequency regulation: during daytime, when most of charging processes take place at public charging spots, the scarcity of the latter lefts not enough time for compensate a deviation in *"decrease charge"* direction and so the related band is very limited.

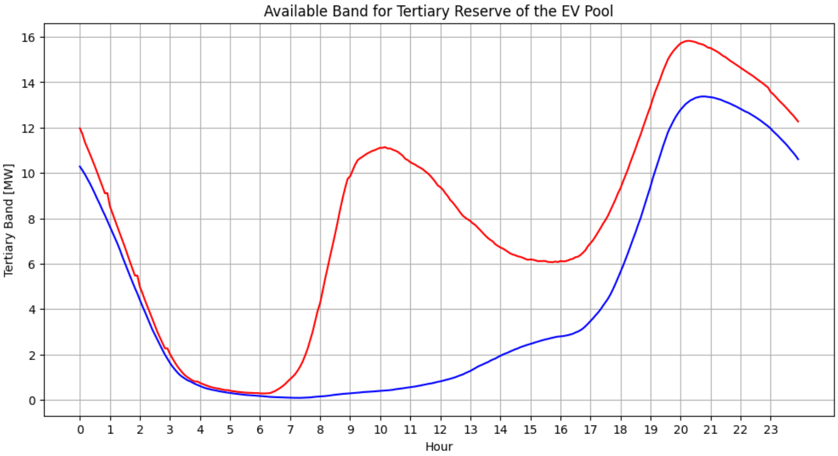


Figure 4.10: Tertiary reserve service available bands

Regarding the calls to provide tertiary reserve, in Table 4.4 and Table 4.5 are reported, as an example, the acceptance probabilities for *"decrease charge"* and *"increase charge"* direction respectively. Values in the tables results from a simulation with as an input the bands represented in Figure 4.10 and offers with a price deviation of 10% with respect to market electricity price.

Probability of being accepted in "decrease" direction							
Hour of the year	1	2	3	...	22	23	24
Probability [%]	2.70	2.46	2.46	...	2.95	3.03	3.25

Table 4.4: Example of acceptance probabilities in "decrease charge" direction

Probability of being accepted in "increase" direction							
Hour of the year	1	2	3	...	22	23	24
Probability [%]	2.09	2.08	2.02	...	2.13	2.13	2.11

Table 4.5: Example of acceptance probabilities in "increase charge" direction

Starting from the probabilities just reported, it is possible to derive the number of calls for each day of the year, as shown in Figure 4.11.

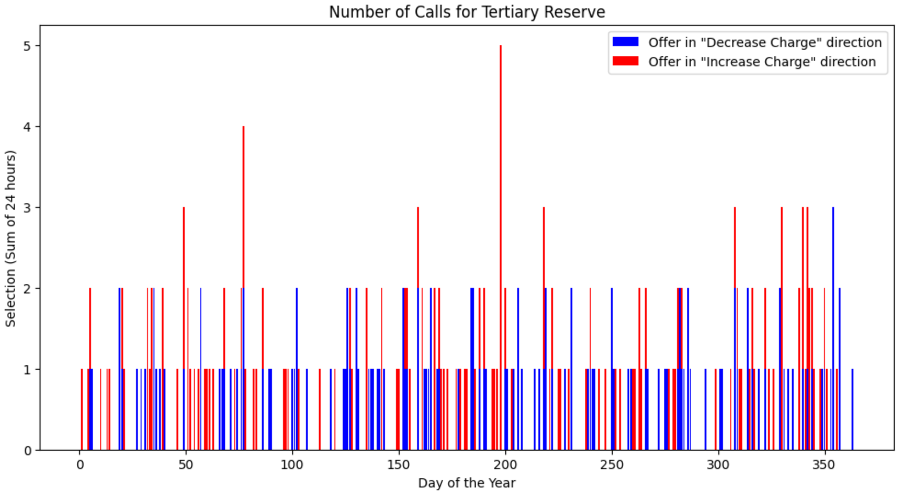


Figure 4.11: Number of calls to tertiary reserve provision

In Figure 4.12 is reported the comparison between the load profile generated by the EV pool without any participation to tertiary reserve provision and the added load after tertiary reserve provision. It is remarkable how as described in (subsection 3.12.4), after a deviation from the original load profile (or set point), the aggregate naturally generates a deviation in the opposite direction in the following time windows in order to respect the constraint on total delivery of requested energy by each single travel.

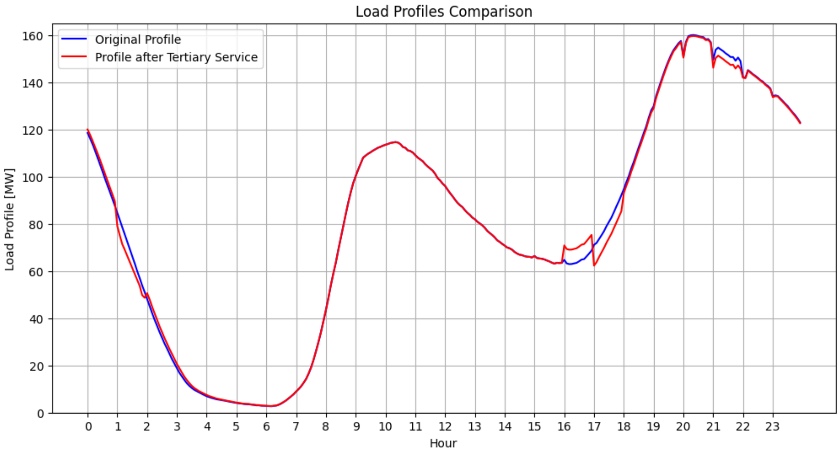


Figure 4.12: Load profile before and after tertiary reserve provision

Along all the described methodology each single charging process is updated to deliver required services and respect designed constraints. In Figure 4.13 two different travels are reported as a meaningful example. *"travel 1"* describes a travel charging charging point with a nominal power output of 6 kW, providing tertiary reserve in *"increase charge"* direction between its charging start and 5 p.m. while *"travel 2"* depicts a *"Return Home"* travel charging at a domestic charging spot with a nominal power of 6 kW providing different services in different directions along the charging time. It can be noted how at the end of each process there is a time frames where the power output is considerably lower due to the compensation for the energy missing during the provision of tertiary reserve in *"decrease charge"* direction.

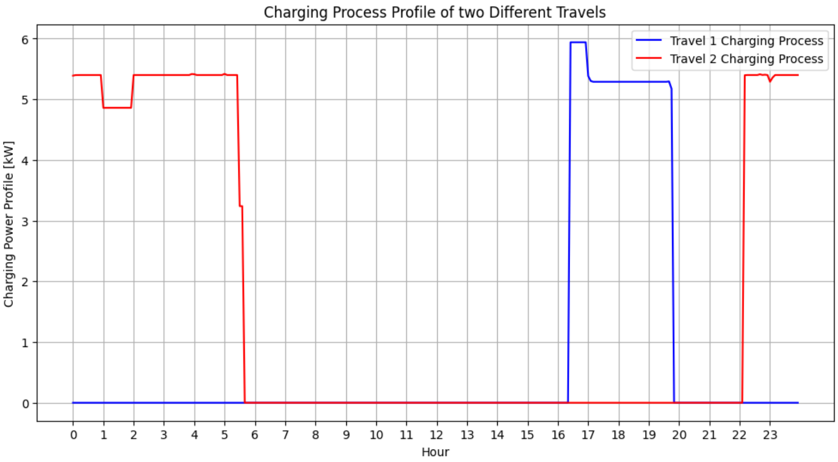


Figure 4.13: Charging processes of two EVs in the aggregate

4.4. Simulation 2

The peaks associated with the added load are higher since, not having to offer flexibility in *"increase charge"* direction, no preventive limitation on power output is applied. The computation method is analogue to the one described for the first simulation presented, the total load profile is obtained by summing up contributions from each single charging process according to the **power list** variable.

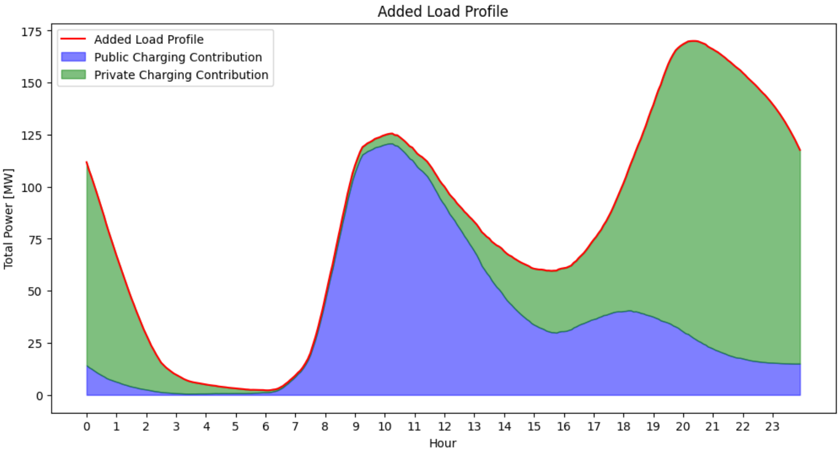


Figure 4.14: Added load profile with contributions from public and domestic charging

With current regulation to participate in the provision of primary frequency regulation it is necessary to offer flexibility in both increase and decrease directions. For this reason the setting with only *"decrease charge"* option would not be enabled to participate in the market for what concerns this kind of service. However, since technologies and regulation are rapidly evolving, in Figure 4.15 and Figure 4.16 (and in all the following simulation with only *"decrease charge"* setting) it is still reported the available primary band that could be offered in the only admitted direction.

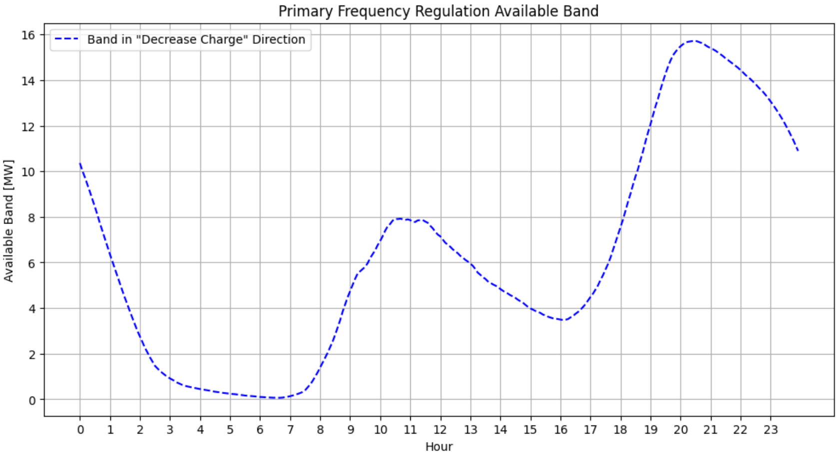


Figure 4.15: Primary frequency regulation available bands

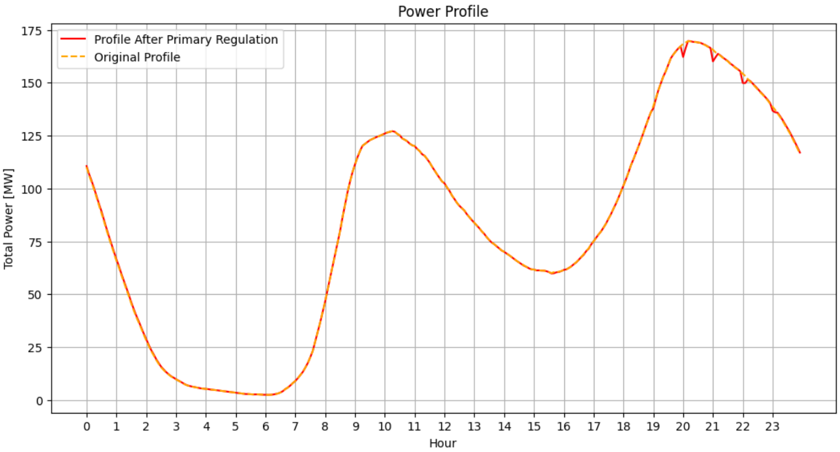


Figure 4.16: Load profile before and after primary frequency regulation provision

In contrast to primary frequency regulation, tertiary reserve can be provided unidirectionally by placing bids exclusively in the selected direction of service. In Figure 4.17 it is reported the available band only in *"Decrease Charge"* direction, in Figure 4.18 the calls for the service, clearly limited to the allowed direction and in Figure 4.19 the profile after the provision of the service.

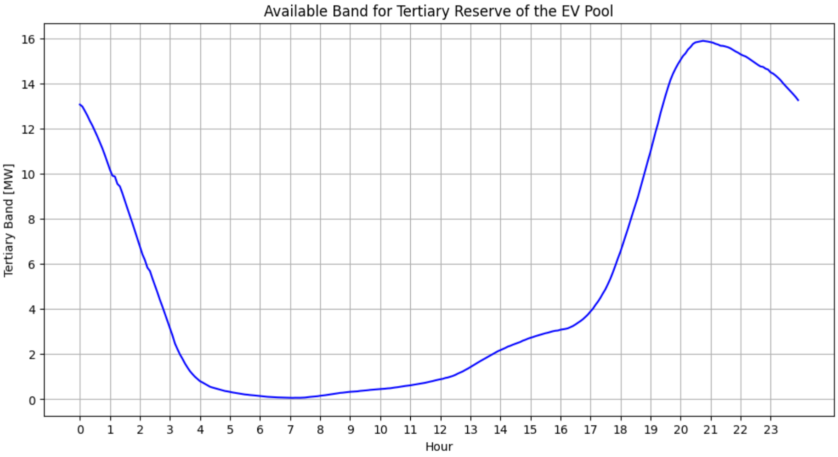


Figure 4.17: Tertiary reserve service available bands

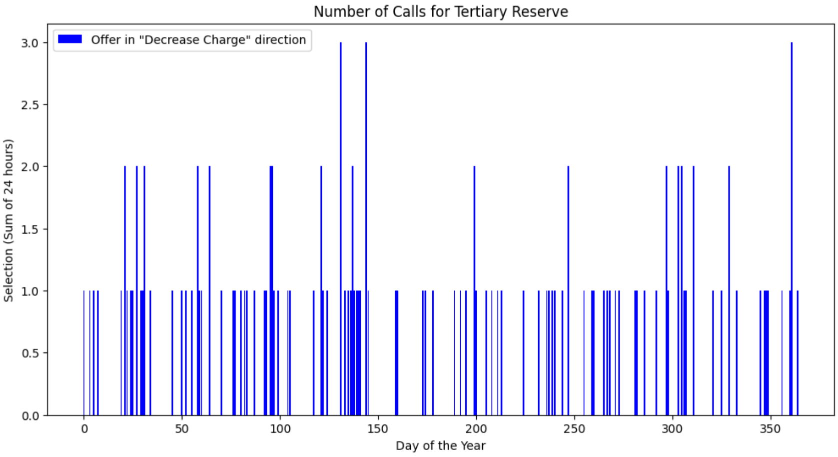


Figure 4.18: Number of calls to tertiary reserve provision

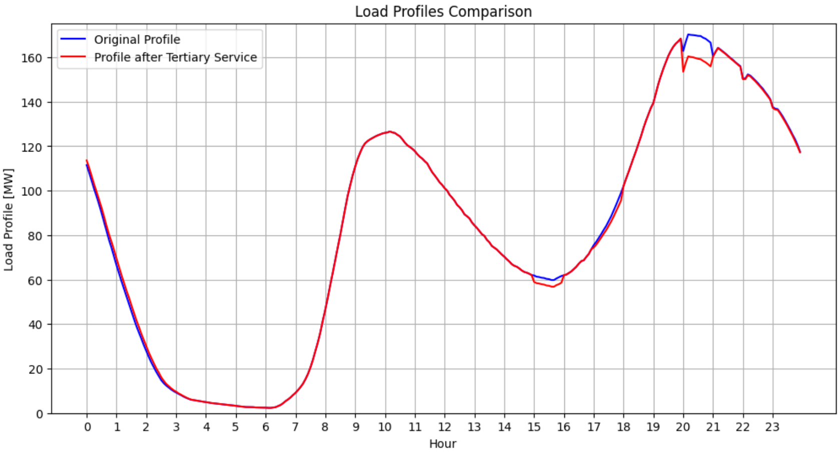


Figure 4.19: Load profile before and after tertiary reserve provision

In Figure 4.20 it is evident how in this configuration the power output of charging spots is not preventively limited to 90% of the nominal one, but it is equal to the latter. the figure provides a clear representation on how primary frequency regulation and tertiary reserve are offered only in *"decrease charge"* direction, and how they impact on the charging process of single vehicles.

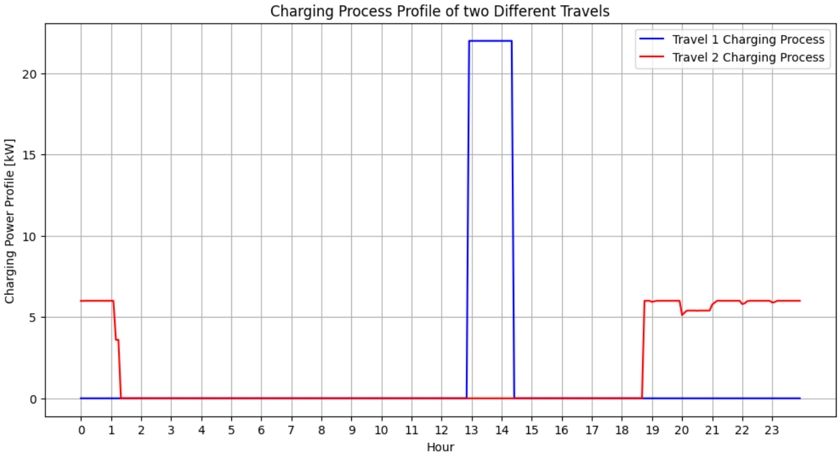


Figure 4.20: Charging processes of two EVs in the aggregate

4.5. Simulation 3

In Figure 4.21 it is displayed the impact of the *"primary bands enhancement"* algorithm on the load profile of the EV pool. It is clear how the highest flexibility margin comes from travels charging at domestic charging points during night time. In fact, this type of travels have generally a far shorter charging time than the assumed stay time (they are reasonably parked all night long) and so can be moved considerably to compensate for the morning minima. Regarding travels charging in public spots during the day, the flexibility margin is much more limited since stay times are shorter and charging points availability presents a particularly restrictive limit.

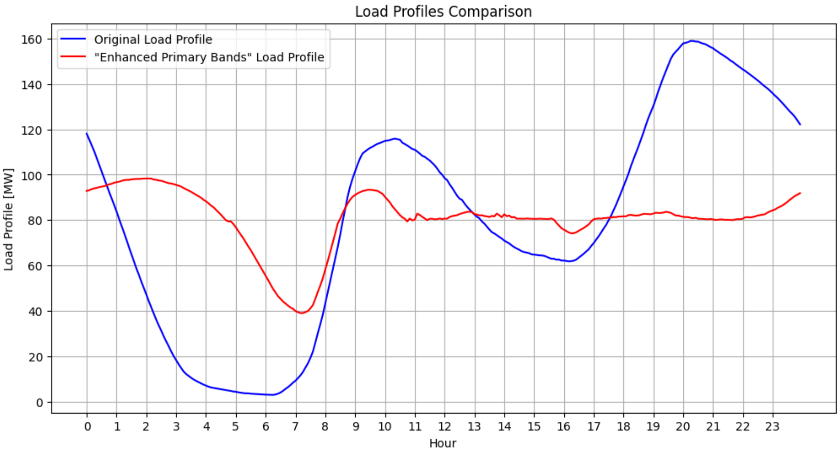


Figure 4.21: Load profile before and after primary bands enhancement algorithm

In Figure 4.22 it is shown how the contribution from charging processes taking place at private charging points and the one from charging session happening in public stations are split.

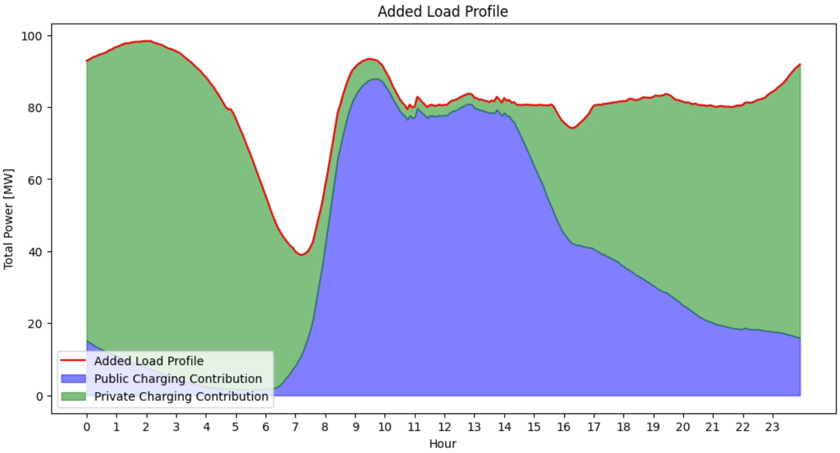


Figure 4.22: Added load profile with contributions from public and domestic charging

Figure 4.23 reports the impact of the *"primary bands enhancement"* algorithm on the primary frequency regulation available bands. Since the quantity that can be bid on the market is equal to the deviation that can be always guaranteed independently of time and direction, it is computed as the minimum of the two bands (in increase and decrease directions), the beneficial effect of the algorithm is evident especially during all the first part of the day, with the only drawback of reducing the available band in the last four hour time frame of the day.

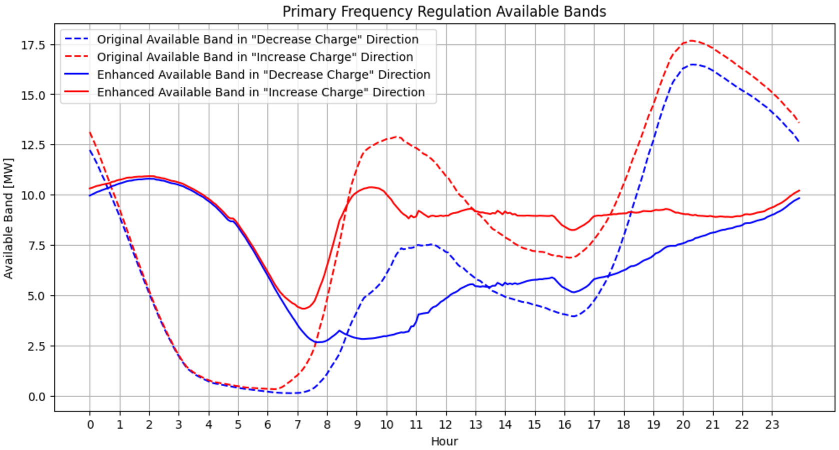


Figure 4.23: Primary frequency regulation available bands

In Figure 4.24 it is shown response of the aggregate to the primary frequency regulation calls as deviations from the original set point.

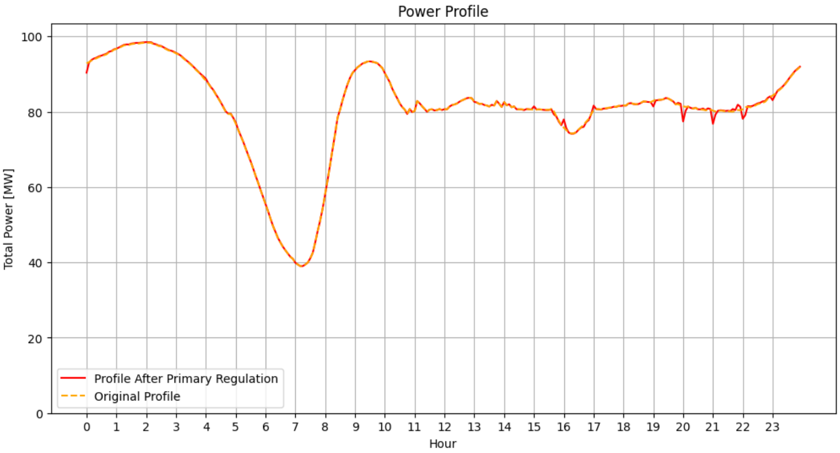


Figure 4.24: Load profile before and after primary frequency regulation provision

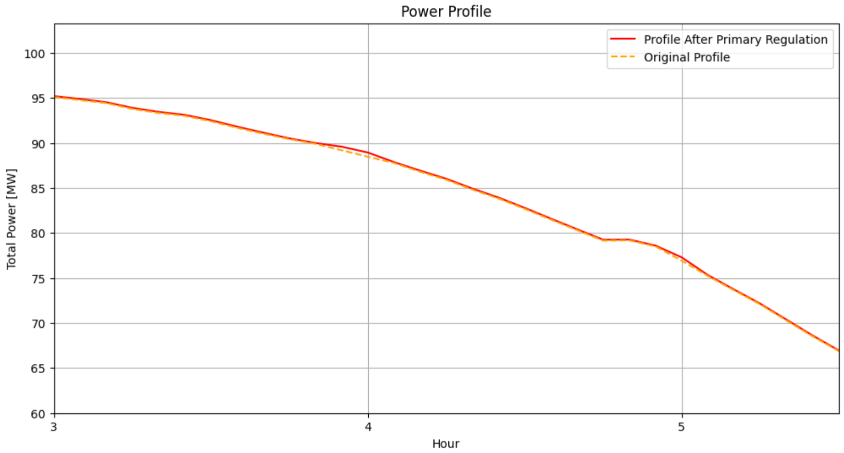


Figure 4.25: Detail of response at 4 and 5 a.m

From Figure 4.9 the frequency deviation appears relevant at the beginning of hours 4 and 5 but the response depicted in Figure 4.24 shows only a slight deviation from original profile, as shown in Figure 4.25. The reason is that the model checks for the capability of the aggregate to provide instant by instant the power deviation required, but then in the profile plot it counts the overall energy deviation and reports the new value for each five minutes time frame. This to be coherent with traffic model time resolution and avoid excessive computational burden. Frequency peaks in the morning have a particularly short duration, so despite the significant power deviation requested the deviation in terms of energy is moderate.

For what concerns bands for tertiary reserve provision, (shown in Figure 4.26) the *"primary bands enhancement"* algorithm does not present a significant improvement, since it is designed specifically for the optimization of primary frequency control bands. *"Decrease charge"* direction band is particularly limited during daytime, since the higher impact on energy delivery of this type of service strongly limits the availability of vehicles. Travels that are finishing their charging process close to their departure time or close to the beginning of a new charging process are not useful for ancillary services provision since their energy needs are prioritised. This last constraint is the responsible for the drop in the band in *"decrease charge"* from 9 a.m. to 2 p.m. where charging processes mostly take place at public charging points. Unevenness present around 4 a.m. are attributable to *"primary bands enhancement"* algorithm application, since travels are pushed close to their departure time and the more restrictive needs imposed by tertiary reserve clash with this behaviour.

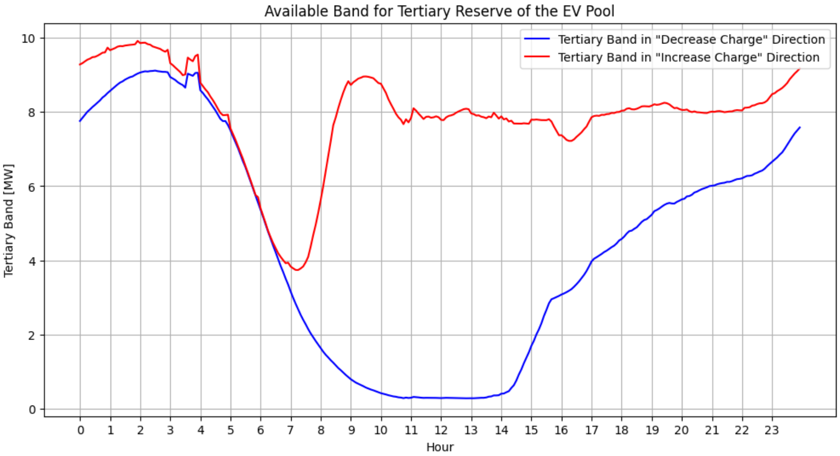


Figure 4.26: Tertiary reserve service available bands

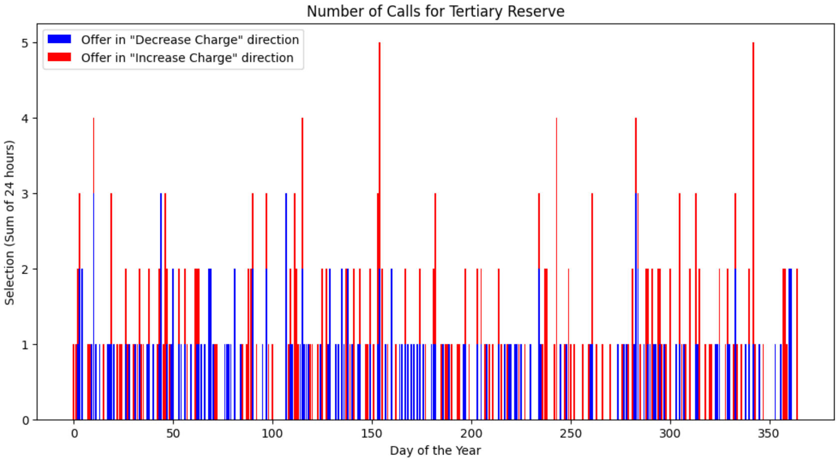


Figure 4.27: Number of calls to tertiary reserve provision

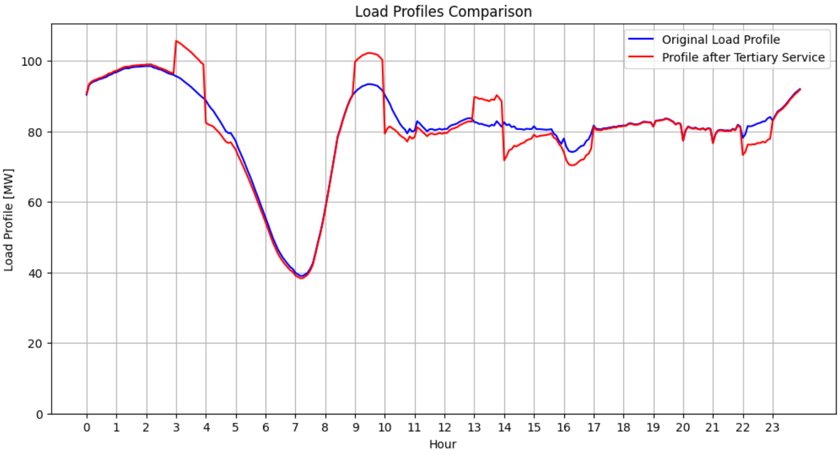


Figure 4.28: Load profile before and after tertiary reserve provision

Figure 4.27 shows the number of yearly calls occurrences for the provision of tertiary reserve, while Figure 4.28 shows the impact of the service on the load profile on the day with the largest number of calls.

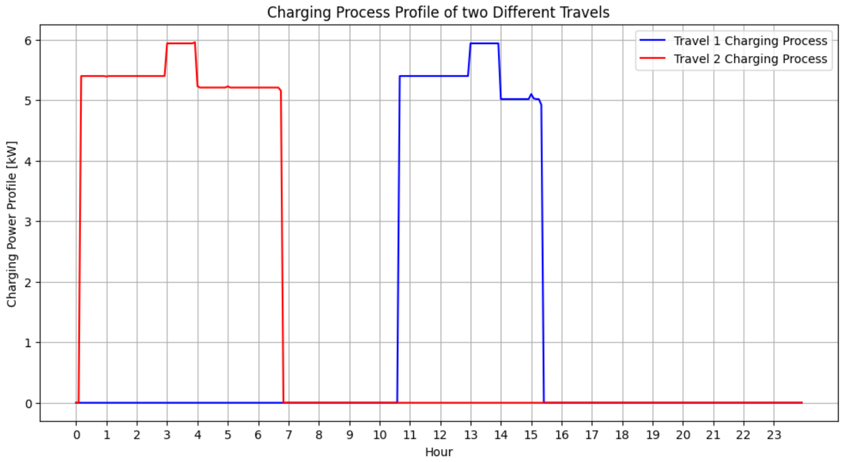


Figure 4.29: Charging processes of two EVs in the aggregate

4.6. Simulation 4

This simulation exhibits a behaviour similar to the earlier one, however, it only provides flexibility in the *"decrease charge"* direction. As a result, there is no preemptive restriction on charging power, leading to typically shorter charging duration. Consequently, charging processes moved by the *"primary bands enhancement"* algorithm to fill in the morning valley present a shorter charging time and can be moved closer to their departure time in the morning. This leads to a smoother load profile with respect to *Simulation 3*, as shown in Figure 4.30.

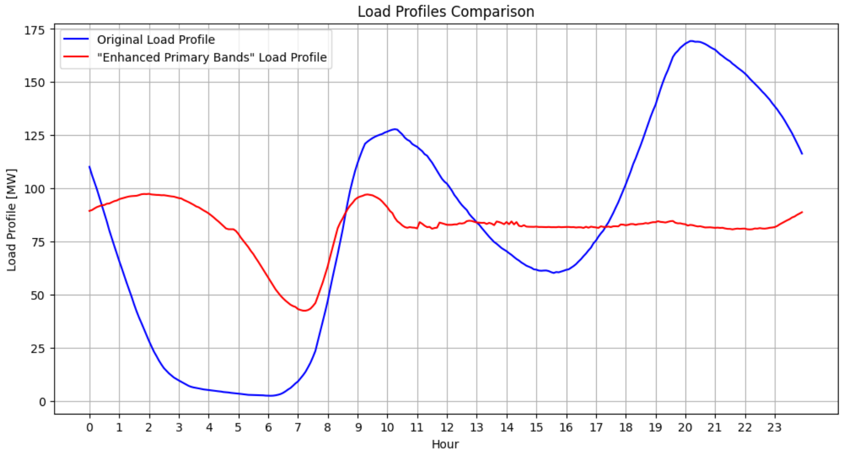


Figure 4.30: Load profile before and after primary bands enhancement algorithm

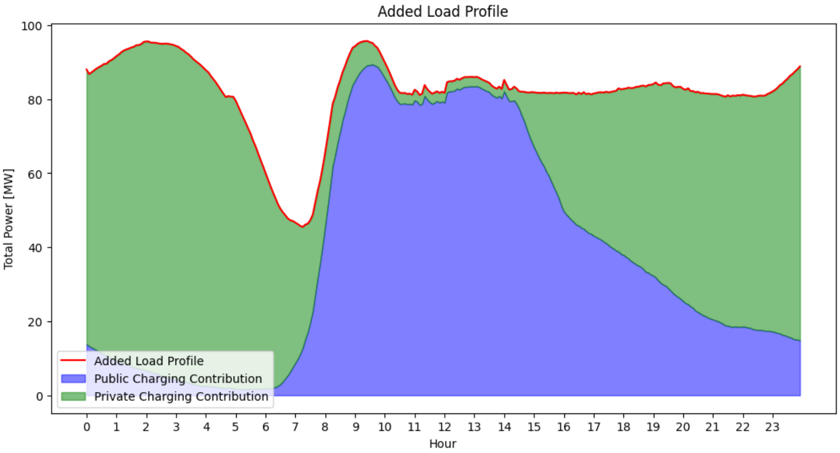


Figure 4.31: Added load profile with contributions from public and domestic charging

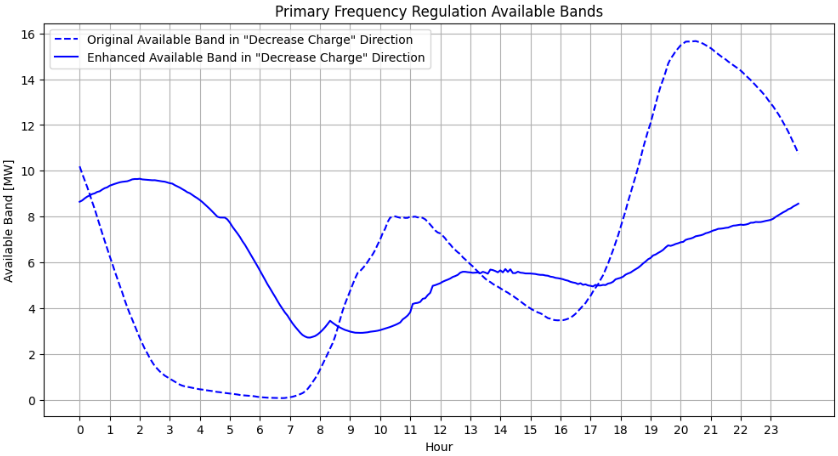


Figure 4.32: Primary frequency regulation available bands

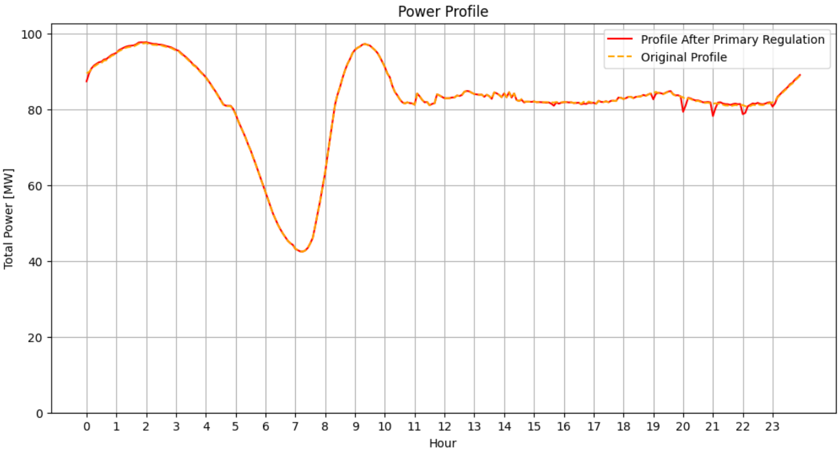


Figure 4.33: Load profile before and after primary frequency regulation provision

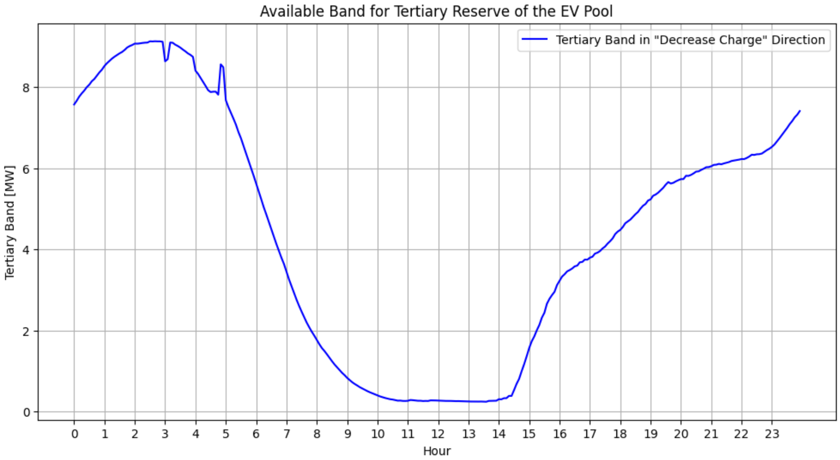


Figure 4.34: Tertiary reserve service available bands

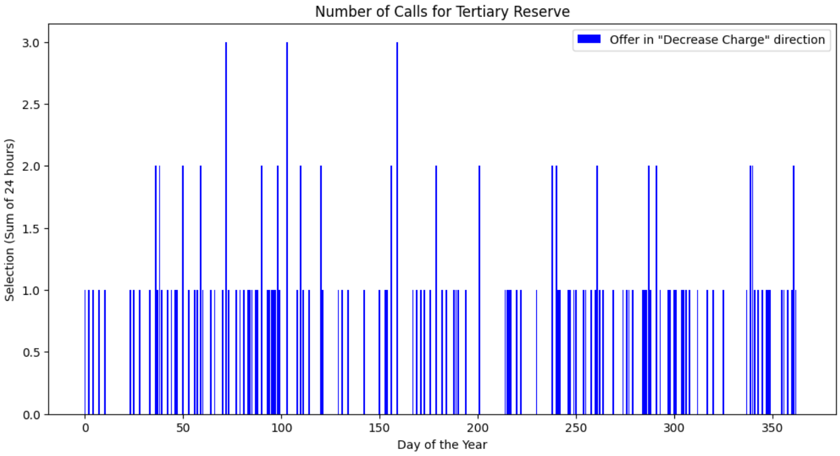


Figure 4.35: Number of calls to tertiary reserve provision

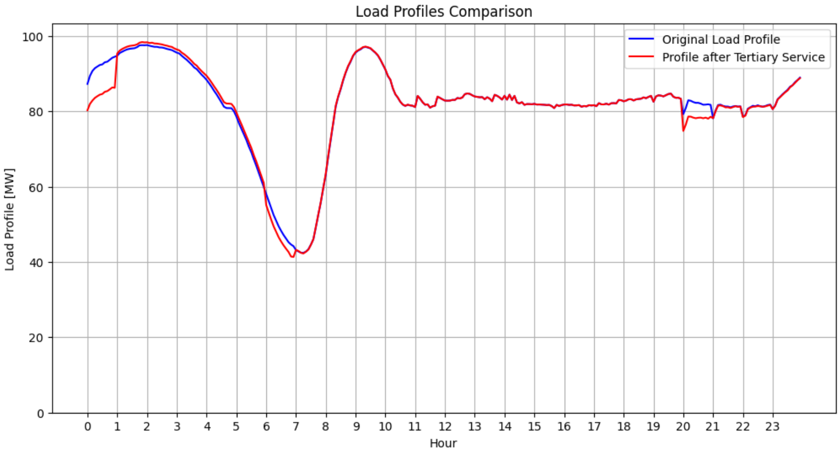


Figure 4.36: Load profile before and after tertiary reserve provision

As depicted in Figure 4.33 and Figure 4.36 this configuration is able to effectively provide both primary frequency regulation and tertiary reserve. However its strong limitation is being able to provide the services only in one direction. The greatest advantage of this approach is that the impact on charging time is extremely limited (an increase of few minutes), since charging points are operated at nominal power. However since primary frequency regulation is currently ruled as a bidirectional service, the aggregate in such a configuration would not be allowed to participate in the market for that service.

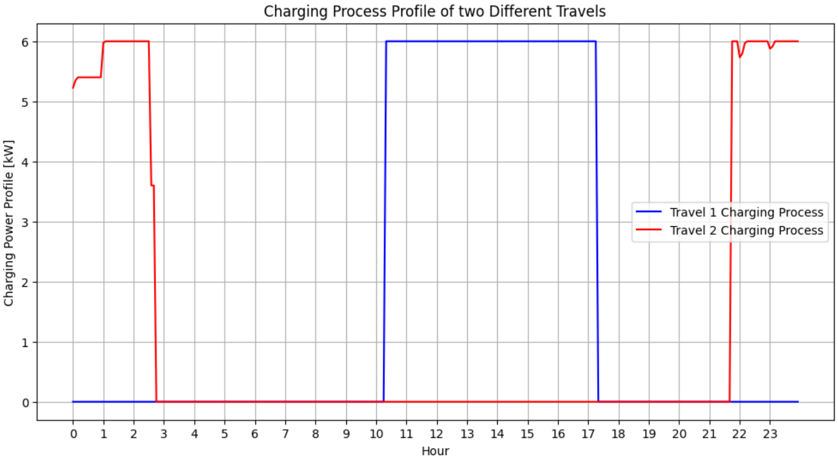


Figure 4.37: Charging processes of two EVs in the aggregate

4.7. Simulation 5

The following simulations include the logic described in subsection 3.12.4, where deviations due to the provision of grid services are absorbed by vehicles via a change in the total energy delivered at the end of the charging process. This way no unwanted unbalance is generated after the provision of a service.

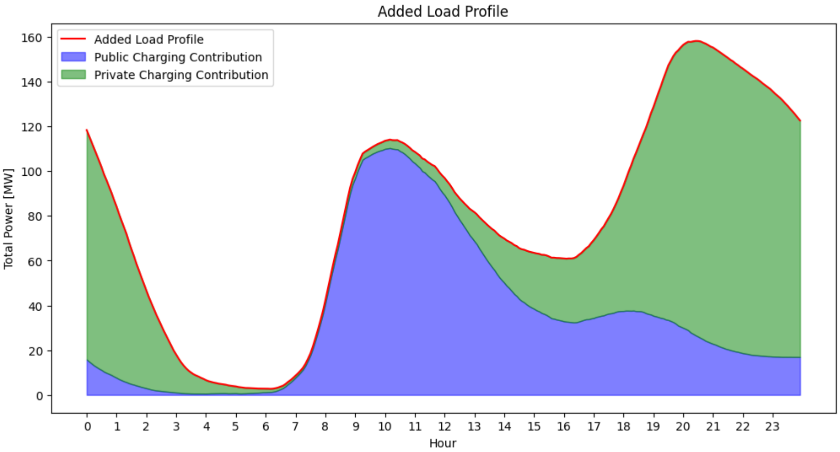


Figure 4.38: Added load profile with contributions from public and domestic charging

The relaxation in the constraint regarding the full delivery of energy requested by each vehicle results in an increase in the values of available bands, both in increase and in decrease direction. As evident from Figure 4.39 and Figure 4.41 the limitation from 80% to an extra 10% of energy requirement delivered at the end of the charging process permits to have a band that coincides with the 10% of the load profile both in increase and decrease. This means the constraint on band values, both for primary frequency regulation and tertiary reserve, is dependent only on the limit in power modulation adopted by the methodology proposed.

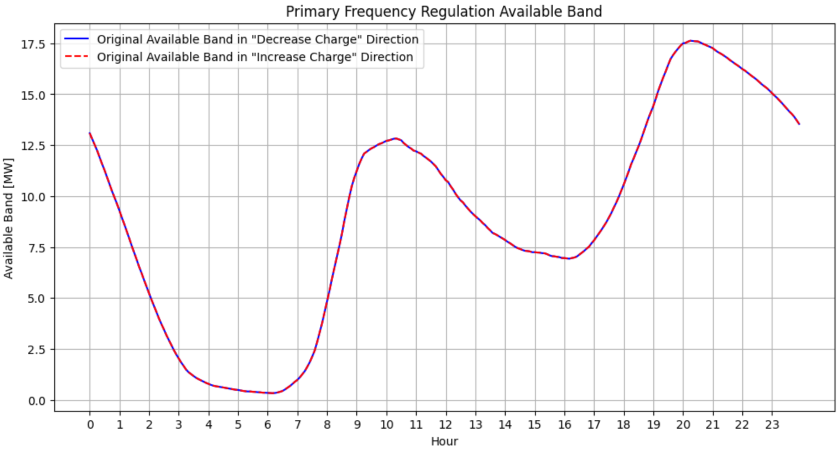


Figure 4.39: Primary frequency regulation available bands

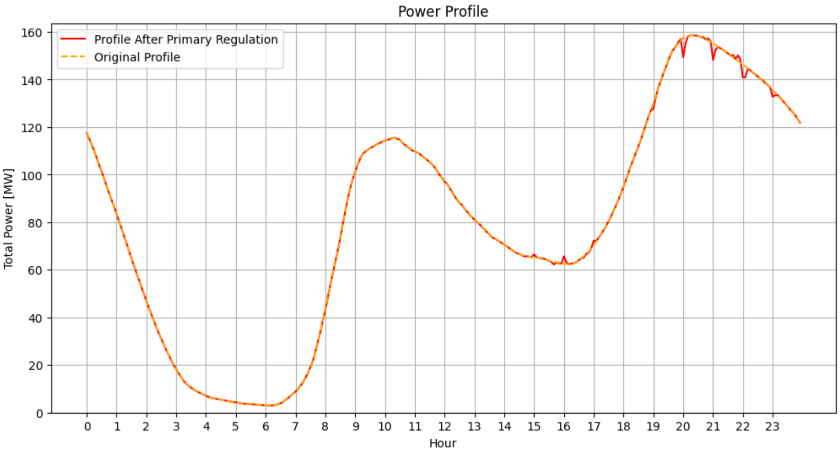


Figure 4.40: Load profile before and after primary frequency regulation provision

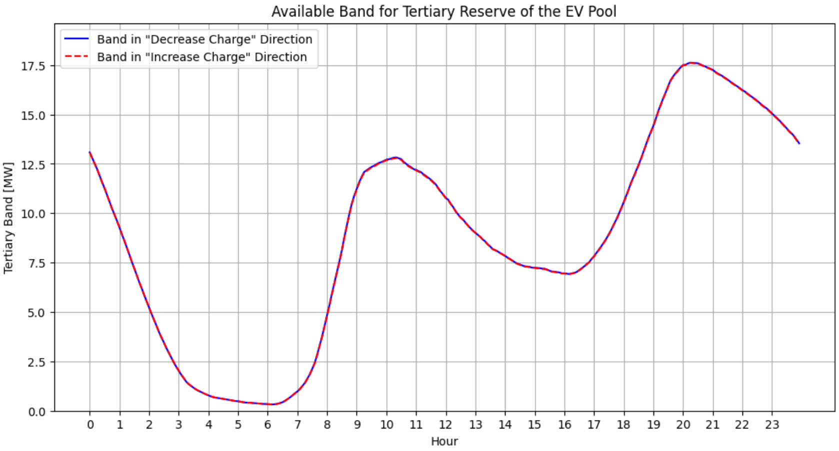


Figure 4.41: Tertiary reserve service available bands

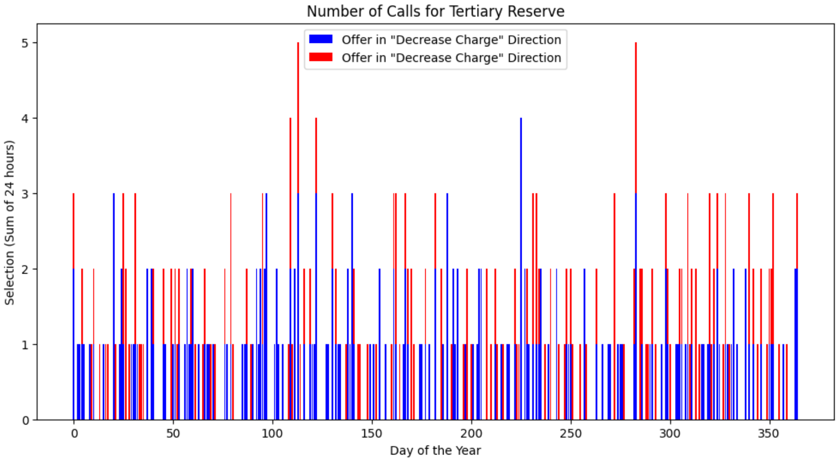


Figure 4.42: Number of calls to tertiary reserve provision

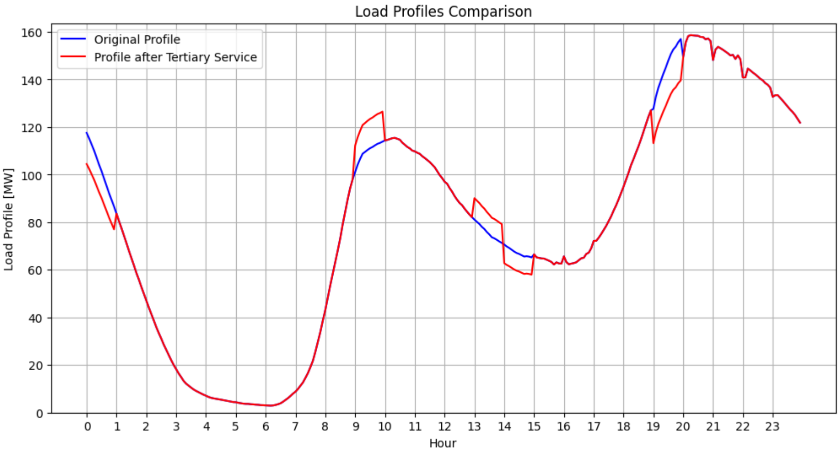


Figure 4.43: Load profile before and after tertiary reserve provision

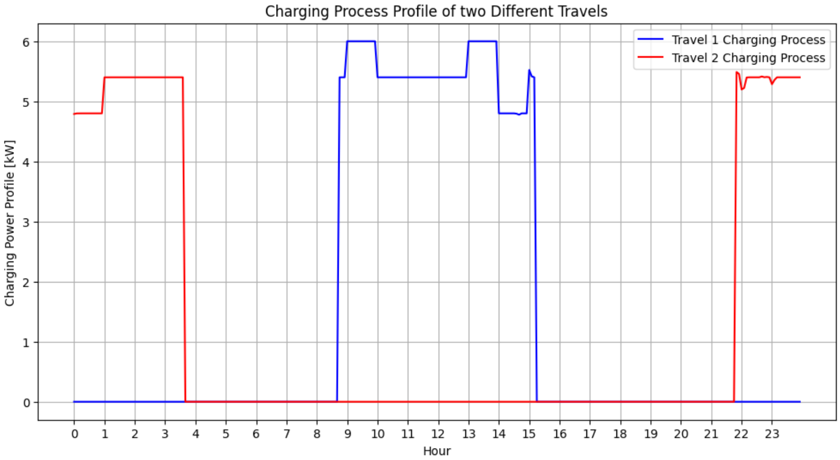


Figure 4.44: Charging processes of two EVs in the aggregate

The plot in Figure 4.39 reports a statistical analysis regarding the impact of grid services on energy delivery for vehicles belonging to the aggregate. The result reported is referred to the day with the largest number of calls for tertiary reserve provision, so the day with the largest impact on charging processes. It is evident how the majority of EVs involved in services provision receive between 1 and 5% less energy than the required one while another consistent number of EVs charge between 5 and 10% more energy than the asked one. This outcome indicates that the effect on electric vehicle owners is minor and would not substantially affect their mobility requirements.

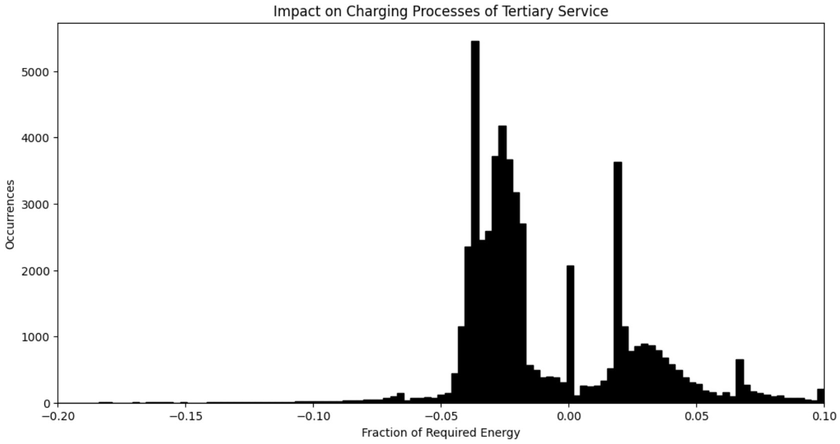


Figure 4.45: Analysis of impact on EV charging processes

4.8. Simulation 6

This simulation models provision of flexibility services only in *"decrease charge"* direction. There is no preemptive restriction on charging power, leading to an increase in peaks load with respect to the previous simulation, as shown in Figure 4.46.

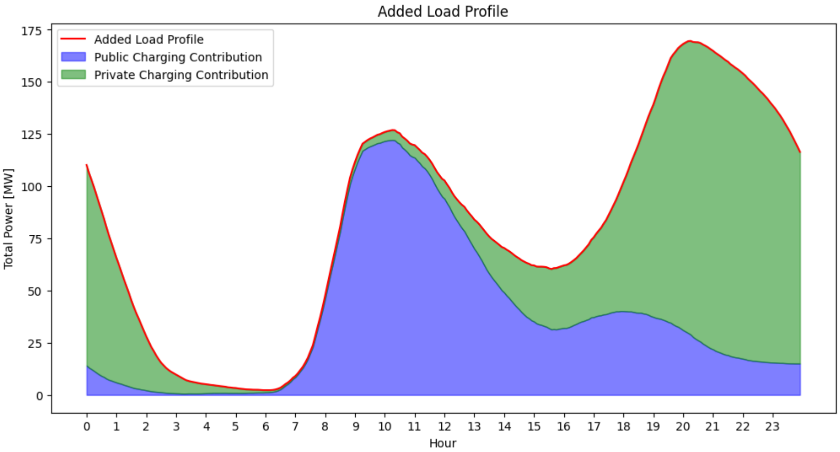


Figure 4.46: Added load profile with contributions from public and domestic charging

Both the band associated with primary frequency regulation (reported in Figure 4.47) and the one associated with tertiary reserve provision (displayed in Figure 4.49) show a similar behaviour to the one described in the previous simulation. Their value is determined by the 10% maximum deviation constraint, that is more restrictive than vehicles energy needs limitations.

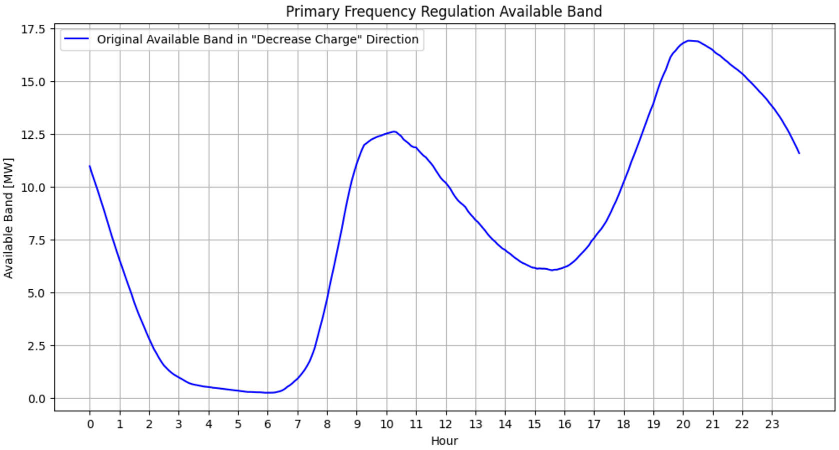


Figure 4.47: Primary frequency regulation available bands

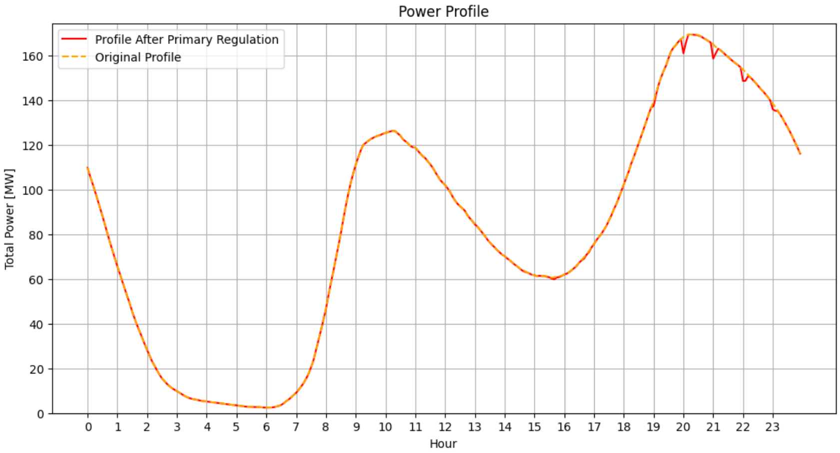


Figure 4.48: Load profile before and after primary frequency regulation provision

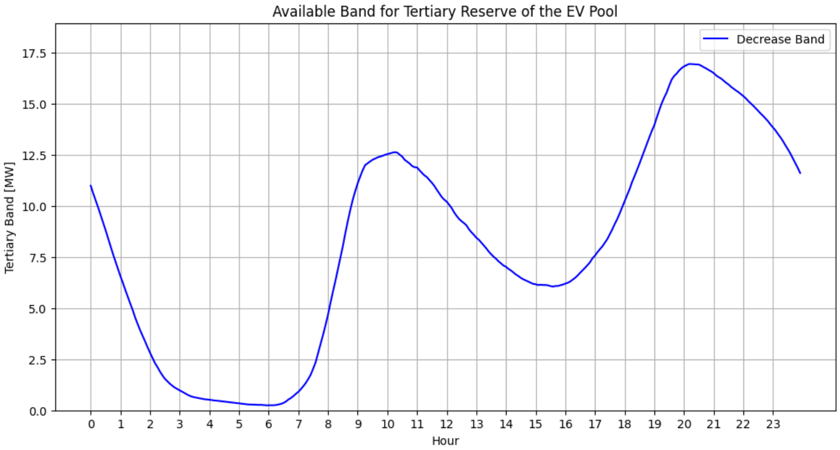


Figure 4.49: Tertiary reserve service available bands

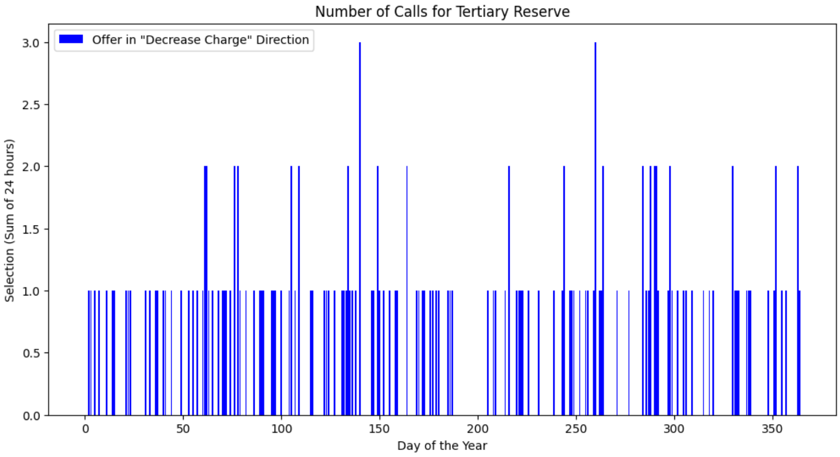


Figure 4.50: Number of calls to tertiary reserve provision

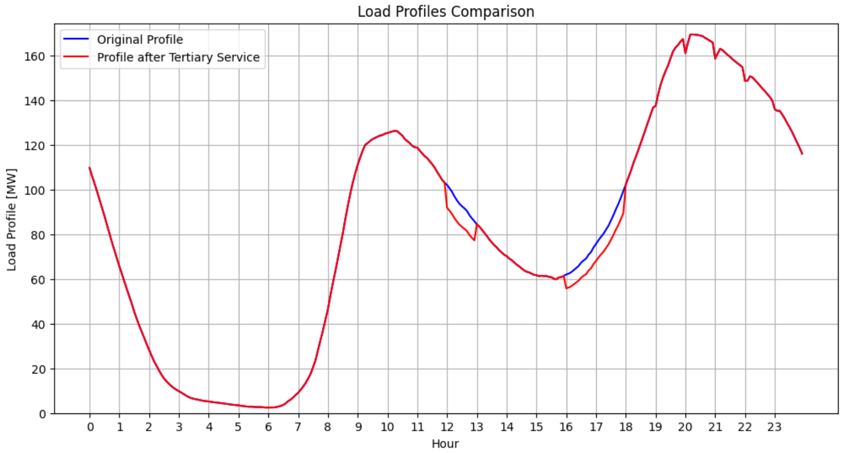


Figure 4.51: Load profile before and after tertiary reserve provision

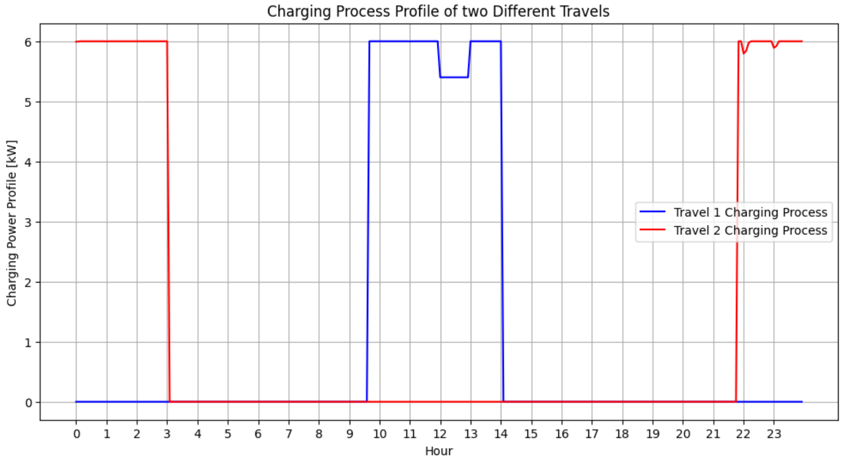


Figure 4.52: Charging processes of two EVs in the aggregate

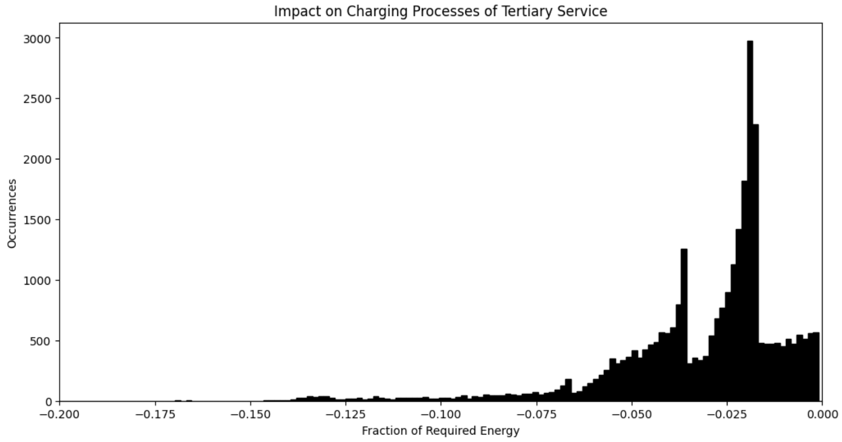
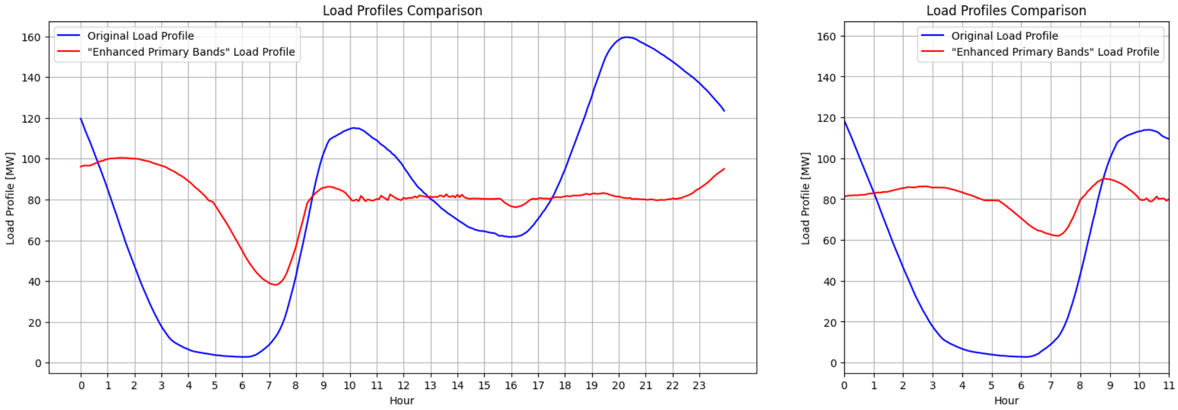


Figure 4.53: Analysis of impact on EV charging processes

The impact on energy delivery in this case, is clearly only negative since flexibility is provided only in *"decrease charge"* direction. The vast majority of vehicles show a delivery lowered by a value between 1 and 5% of their request in the most critical day, confirming the slight impact on energy delivery.

4.9. Simulation 7

To have the slightest possible impact on energy requests the *"primary bands enhancement"* algorithm keeps the constraint of limiting its action until the process is able to fulfill its request. This way the added flexibility given by the relaxation on energy delivery constraints is employed fully for services provision. As it can be noticed from the comparison provided in Figure 4.54 if the *"primary bands enhancement"* algorithm is allowed to move travels up to the 80% of required energy delivery it is able to fill the morning valley more effectively. The problem with this approach is that more than 10’000 travels receives a value close to the 80% of the energy request, that would mean on the one hand a possible relevant impact on their mobility needs and on the other the impossibility to participate to ancillary services provision if the constraint on at least 80% of energy to be delivered must be respected.



(a) No impact on energy delivery (b) 80% limit

Figure 4.54: Primary bands enhancement behaviour with charge impact

Also in this configuration the limitation on bands value is given by the constraint on maximum charging point power output variation. Consequently both primary frequency regulation bands (Figure 4.56) and tertiary reserve bands (Figure 4.58) settle around a value equal to 10% of the load profile. The only time frame when limitation on energy delivery shows its relevance is around 1 a.m. where an oscillation in the bands value can be observed in (Figure 4.58).

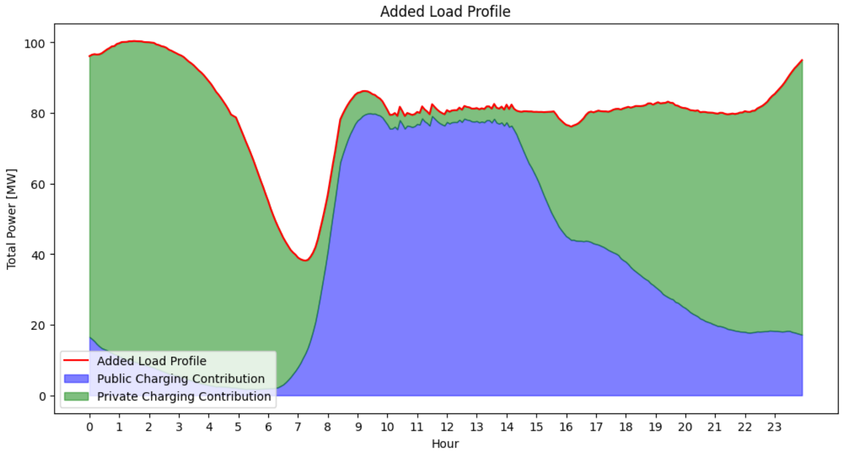


Figure 4.55: Added load profile with contributions from public and domestic charging

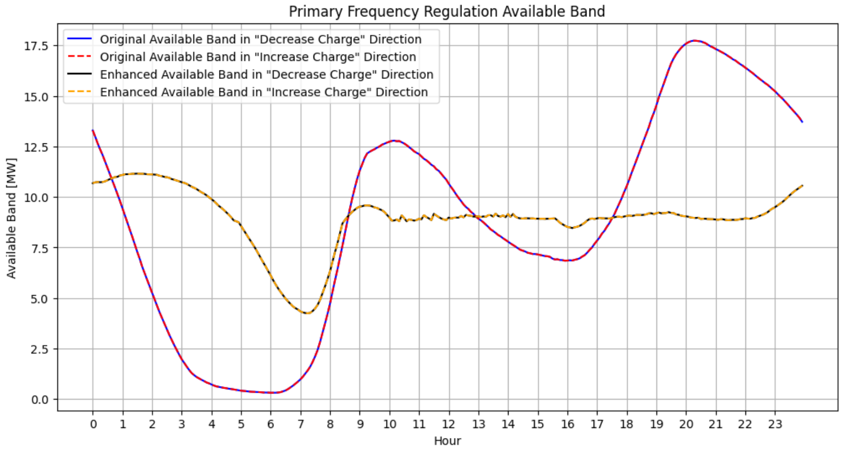


Figure 4.56: Primary frequency regulation available bands

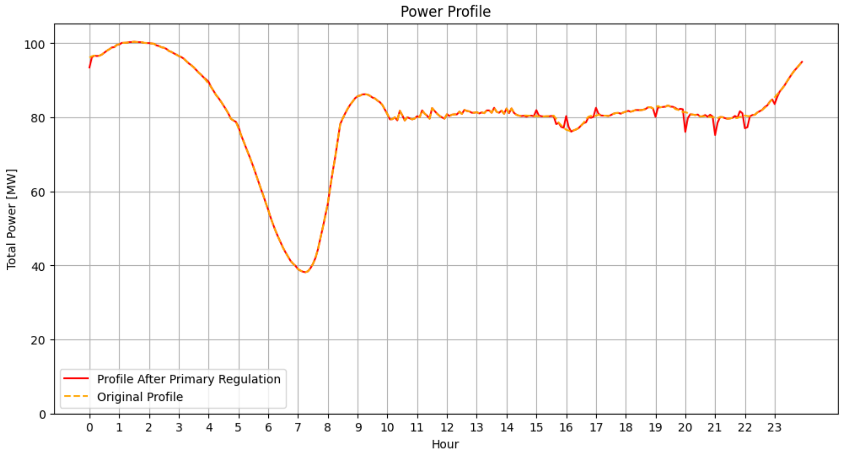


Figure 4.57: Load profile before and after primary frequency regulation provision

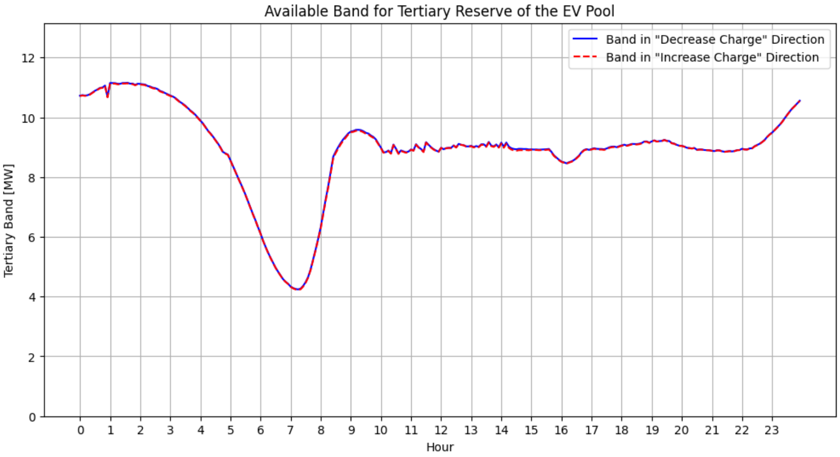


Figure 4.58: Tertiary reserve service available bands

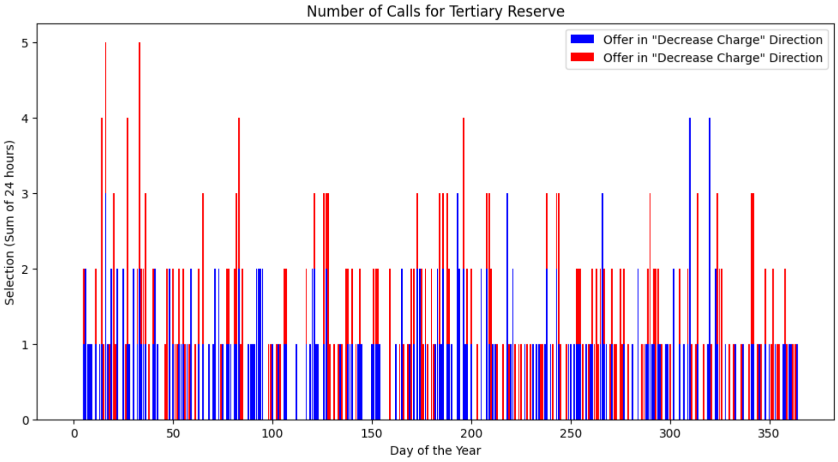


Figure 4.59: Number of calls to tertiary reserve provision

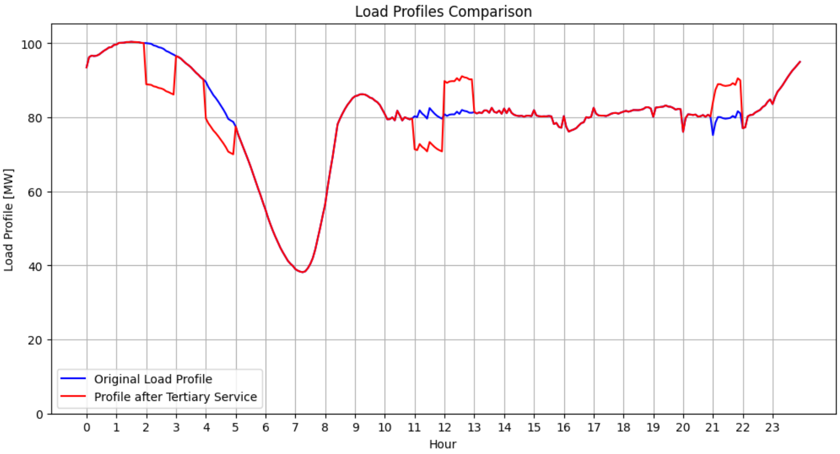


Figure 4.60: Load profile before and after tertiary reserve provision

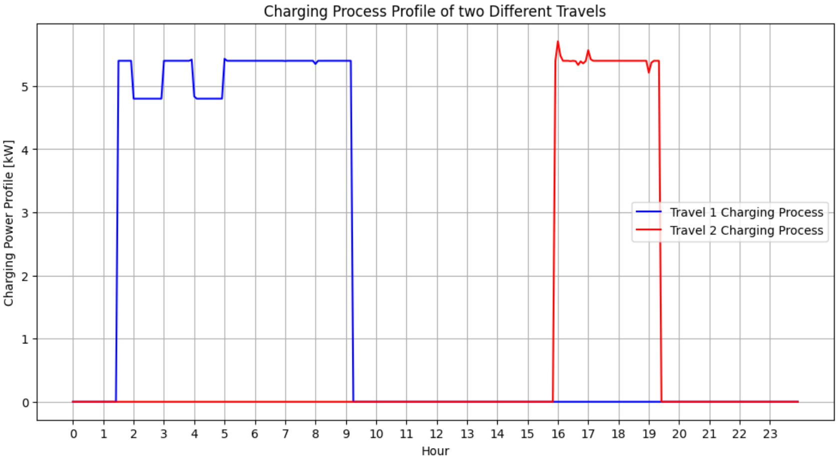


Figure 4.61: Charging processes of two EVs in the aggregate

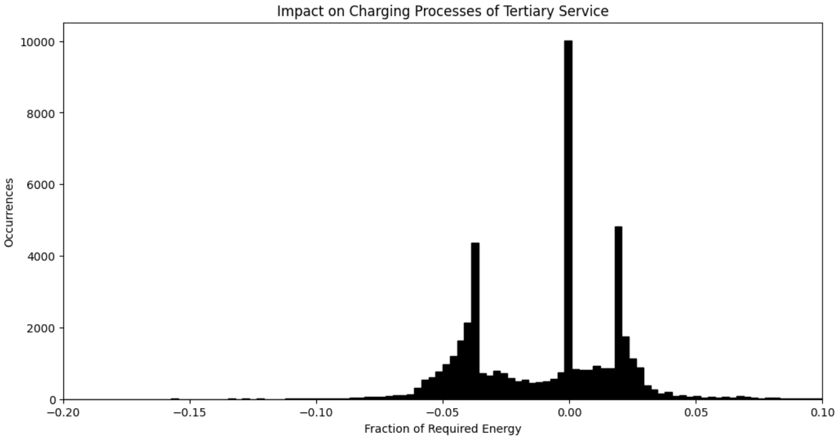


Figure 4.62: Analysis of impact on EV charging processes

Also this simulation confirms the limited impact of modelled services provision on energy delivered to EVs. Almost all vehicles belonging to the simulated fleet show a deviation comprehended between -5 and 5% with respect to the required energy.

4.10. Simulation 8

This simulation depicts a pattern close to the previous one; nonetheless, it exclusively offers flexibility in the *"decrease charge"* direction. This means that charging power faces no preventive limitations, resulting in reduced charging times with respect to previous scenario. Therefore, the *"primary bands enhancement"* algorithm is able to shift charging processes during morning valley closer to their departure time, resulting in an even more uniform load profile (Figure 4.63) than the one obtained in the previous simulation.

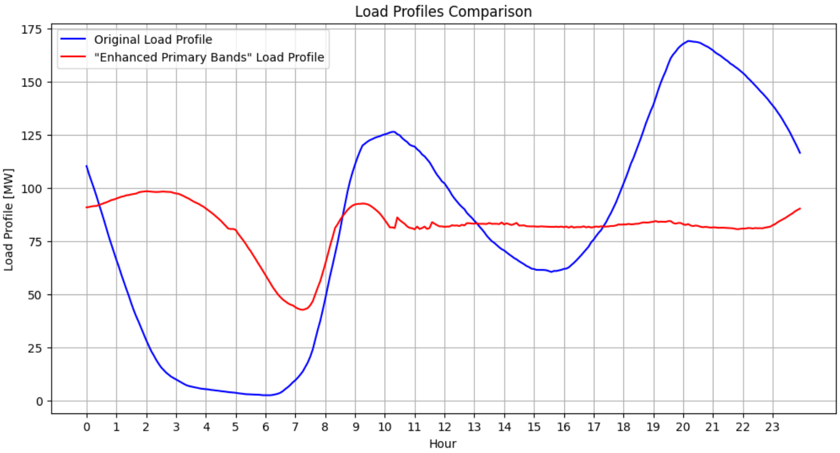


Figure 4.63: Load profile before and after primary bands enhancement algorithm

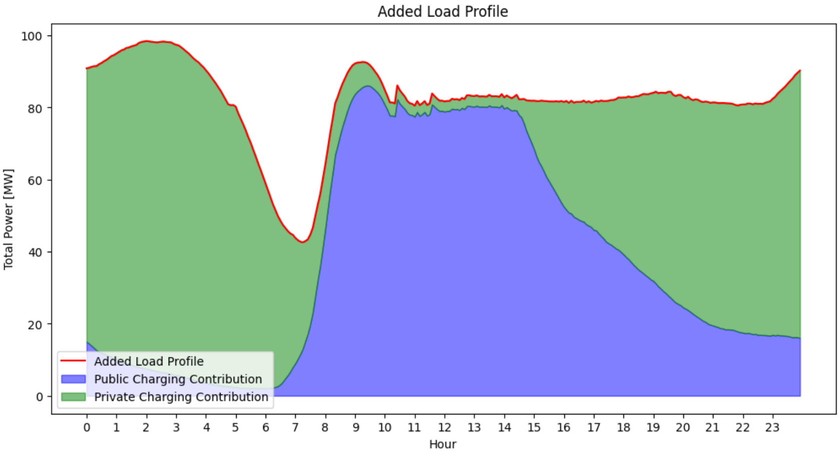


Figure 4.64: Added load profile with contributions from public and domestic charging

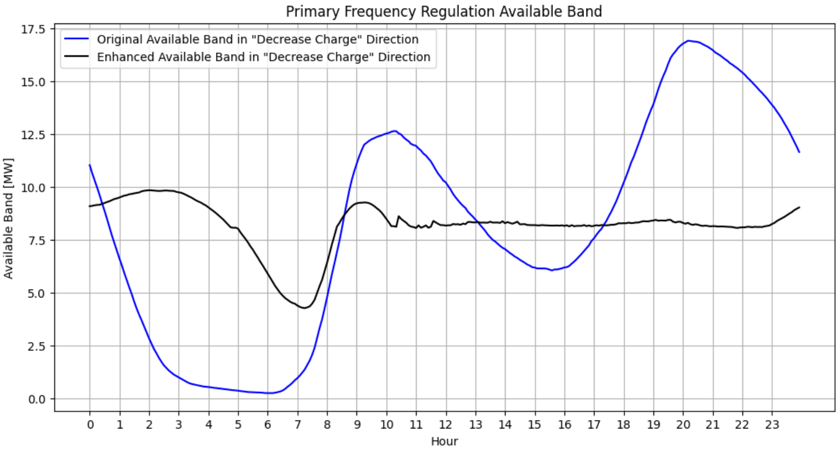


Figure 4.65: Primary frequency regulation available bands

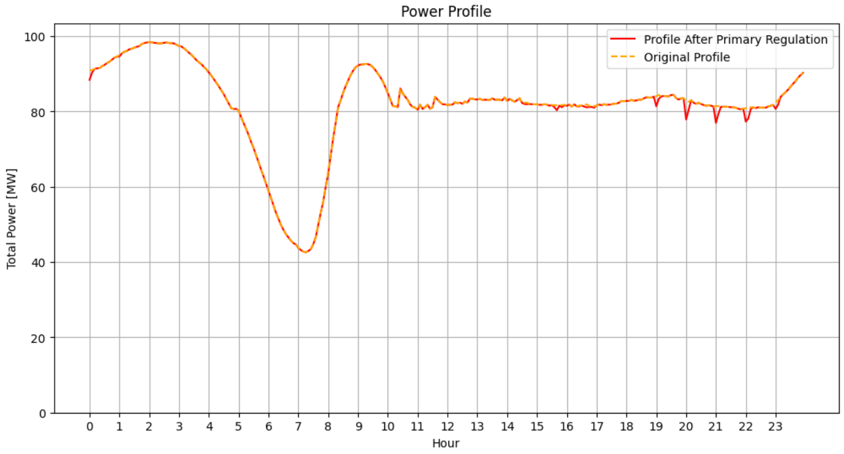


Figure 4.66: Load profile before and after primary frequency regulation provision

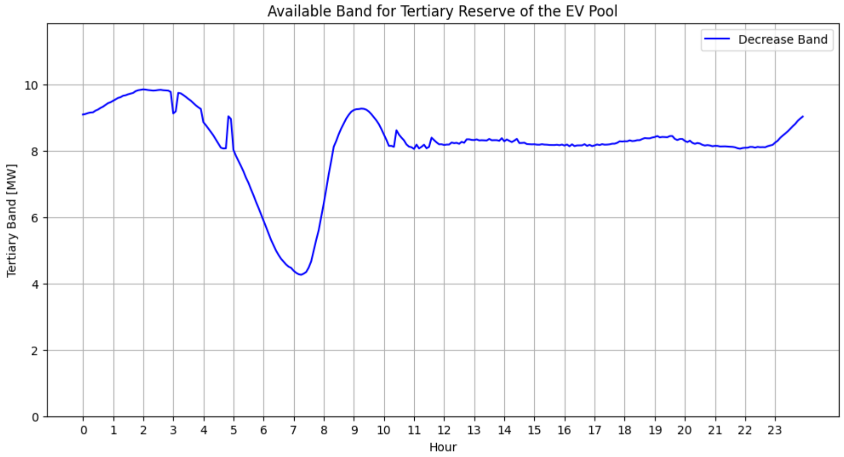


Figure 4.67: Tertiary reserve service available bands

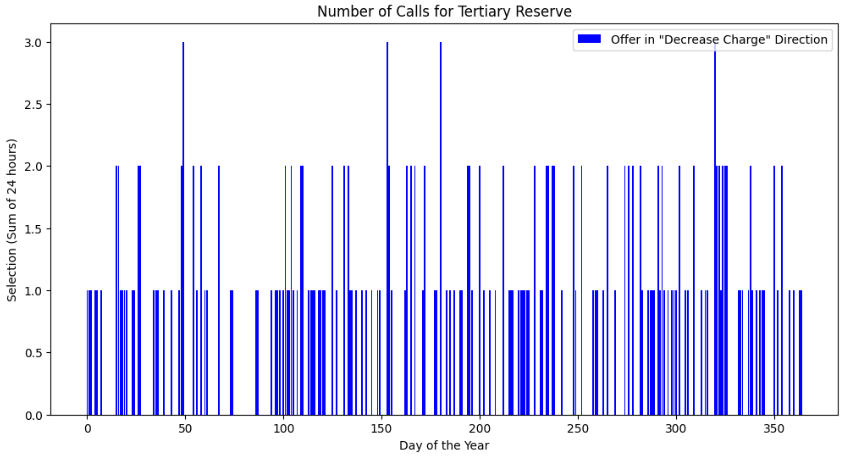


Figure 4.68: Number of calls to tertiary reserve provision

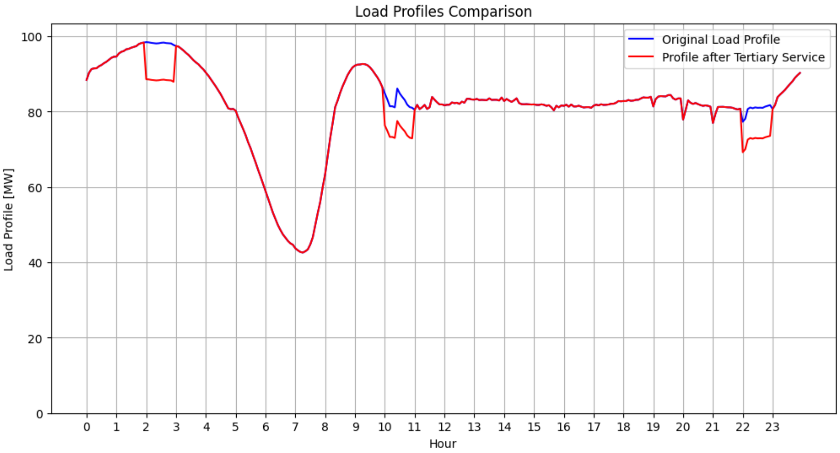


Figure 4.69: Load profile before and after tertiary reserve provision

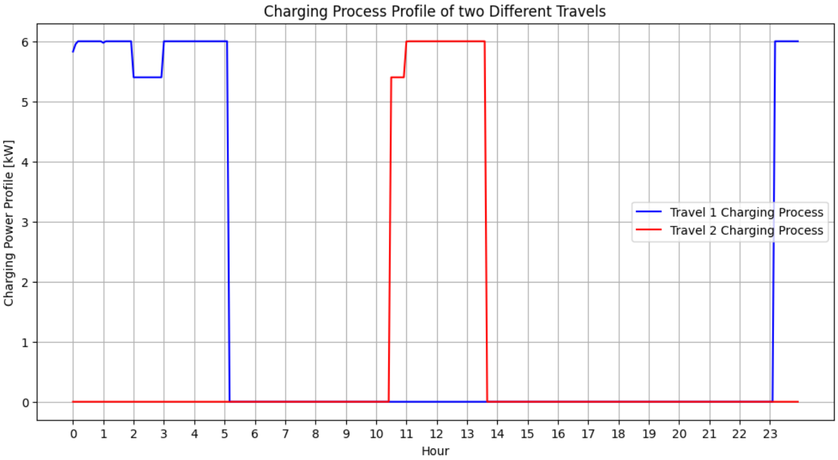


Figure 4.70: Charging processes of two EVs in the aggregate

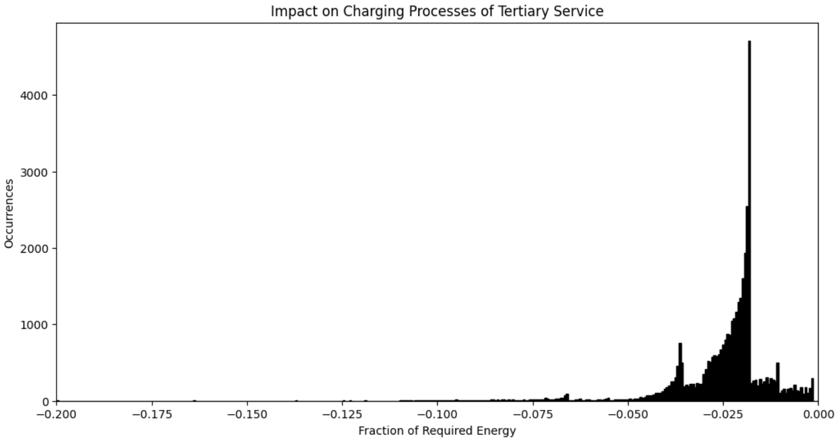


Figure 4.71: Analysis of impact on EV charging processes

The impact on energy delivery is clearly only negative since flexibility is provided only in "decrease charge" direction. The vast majority of vehicles show a reduction below 3% of their request in the most critical day, confirming the extremely reduced impact on energy delivery and the almost negligible one on mobility needs.

4.11. Economic evaluation

To assess the potential revenues generated by the services proposed by the aggregate an economic analysis is performed. Economical values should be assigned to each one of the proposed and evaluated services in order to have an overall estimation of possible revenues for the aggregator.

4.11.1. Primary frequency control

To attribute a value to the offered capacity in terms of primary frequency regulation data from [47] are taken as a reference. In the current Italian regulatory framework no remuneration is corresponded to plants that contribute to primary frequency control since it is imposed as a mandatory service for relevant plants. [47] reports data from the capacity market in central Europe thanks to data from TSOs of those areas (50Hertz for Germany, Tennet for Netherlands). Prices are reported in €/MW, so the band availability is what gets remunerated. These prizes are paid to operators each four hours so to apply them to the analysis performed it is needed to have the computation of the minimum band that can be granted every four hours by the EV pool.

In Table 4.6 required bands availability are reported. The computation performed for each four hours time span is reported in Equation 4.1. The assessment of the minimum band in both directions is essential due to the existing regulatory framework, which mandates that the primary frequency regulation band be available in both directions. Consequently, simulations 2, 4, 6, and 8 are not considered in this part of the economic analysis because they only offer the band in the *"decrease charge"* direction.

$$band = min(min(band\ ''increase\ charge''), min((band\ ''decrease\ charge'')) \tag{4.1}$$

	Time Slot	0-4	4-8	8-12	12-16	16-20	20-24
Simulation 1	Available Band [kW]	768	132	1081	4071	3954	12669
Simulation 3	Available Band [kW]	9776	2662	2755	4839	5150	7582
Simulation 5	Available Band [kW]	833	324	4821	6861	6925	13540
Simulation 7	Available Band [kW]	9991	4241	6325	8579	8459	8848

Table 4.6: Summary of available band for different time slots across simulations

Applying then prices in [47] to the just described bands it is possible to have an estimation of the yearly revenues coming from this kind of service. In Figure 4.72 a chart with the values in object is reported.

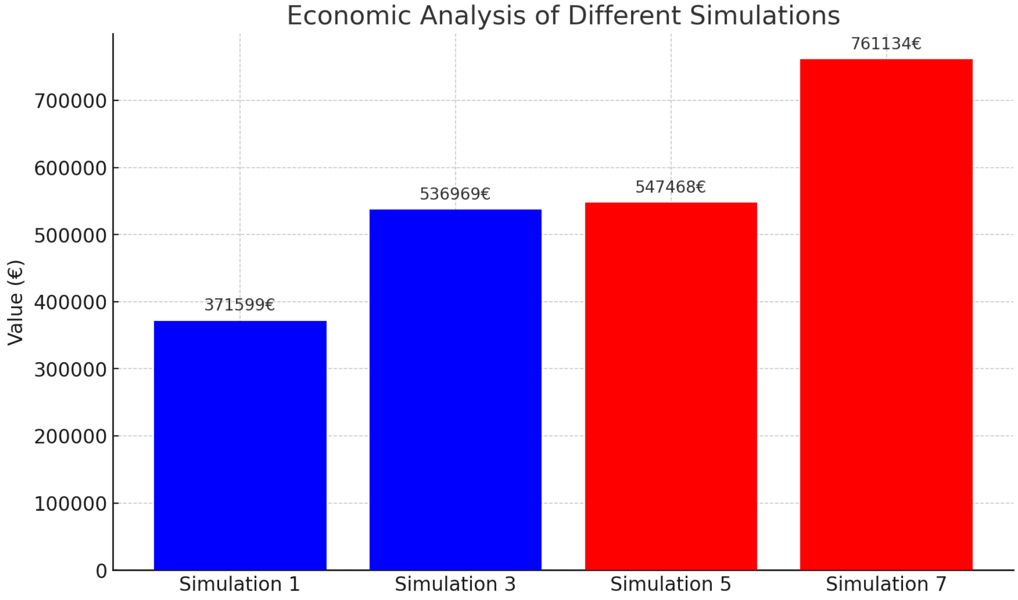


Figure 4.72: Revenues from primary frequency regulation

Bars in blue represent the two simulations with the *"full charge"* logic while in red are shown the two *"impacted charge"* logic ones. The differences between the two blue bars and the two red bars are due to the implementation of the *"primary bands enhancement"* algorithm that leads to a 45% and 39% increase in revenues respectively.

4.11.2. Tertiary reserve service

In the remuneration of tertiary reserve the price deviation from MGP plays a crucial role since it not only influences the margin for the aggregator but has also an impact on the acceptance probability as detailed in subsection 3.12.2. Since the acceptance probability values in current context are already slight it is chosen to keep a low price deviation of 10%. In spite of the competitive price offered the limited value in terms of power that the aggregate can offer drastically limits the yearly number of calls by the TSO. In Figure 4.73 it is reported for each simulation the number of calls in a year in *"increase charge"* and *"decrease charge"* directions. It is important to notice that calls for simulations in *"decrease charge"* mode are fewer since processing charging at full power are faster and so provide availability for a shorter time.

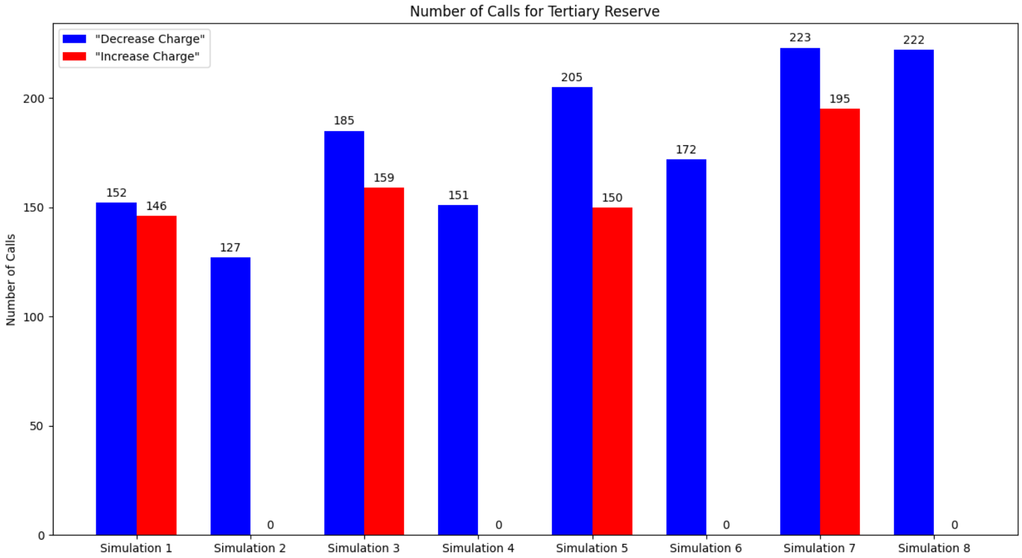


Figure 4.73: Number of calls for tertiary reserve provision

The number of calls for this service is quite low, with no more than 500 calls annually compared to the total of 8,760 hours in a year, as shown in Figure Figure 4.74. This results in relatively low revenues from the service. However, simulations that provide flexibility in both directions (indicated in red) generate more revenue. This increase is due to a significantly higher number of calls, as it represents the total calls made in both directions.

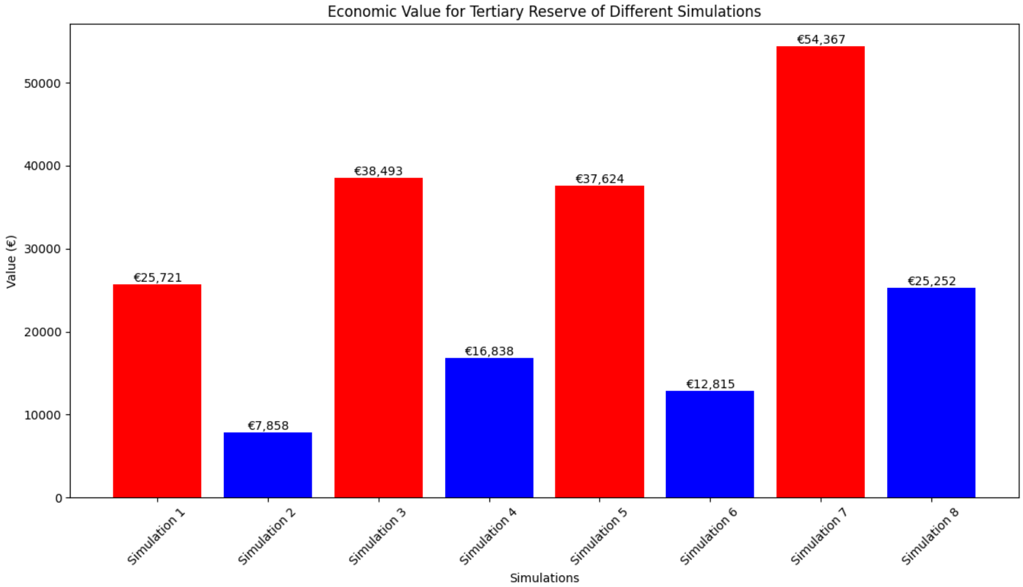


Figure 4.74: Yearly revenues from tertiary reserve provision

4.11.3. Unbalances evaluation

As described in subsection 3.12.4 the TSO applies a penalty to players in the market that do not respect the plan declared in the day ahead. In Figure 4.75 the values of yearly penalties that would be applied to the aggregate are reported. Values are computed running the simulation for all the 365 days of the year combining information on the tertiary calls with prices of MGP and MSD taken from GME website [48]. The most recent 2023 records are employed, using 2022 data for missing months, normalising their values (particularly high due to post - pandemic and geopolitical situation) to capture monthly fluctuations respecting 2023 general trend.

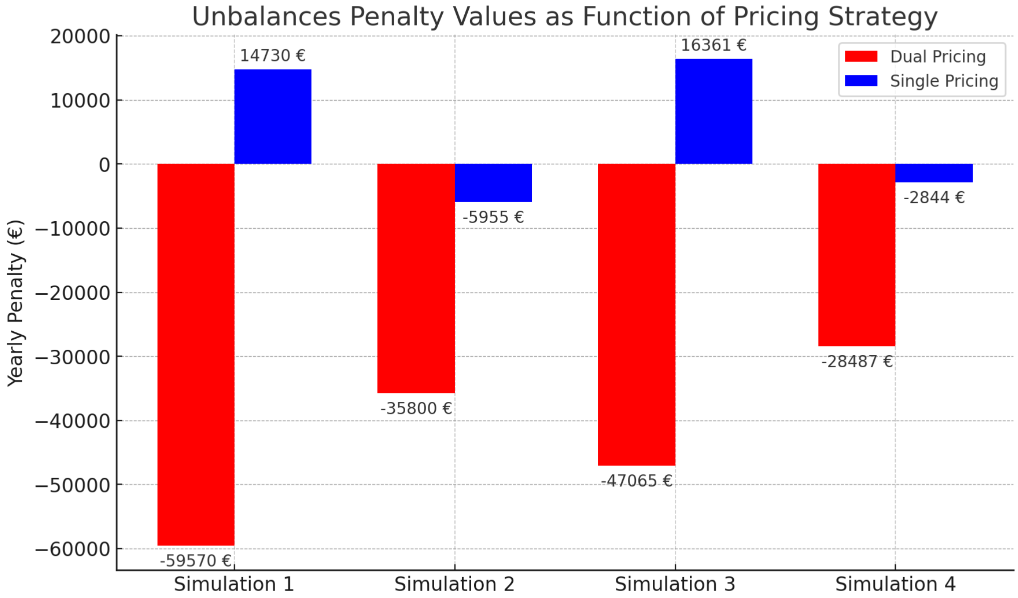


Figure 4.75: Yearly penalty values for unbalances

From the presented chart it is clear how *"dual pricing"* algorithm is far more penalising than the *"single pricing"* one for the aggregate. For simulations offering flexibility in both directions applying the *"single pricing"* logic the aggregate is able to benefit from its own unbalances since the majority of them have the opposite sign than the simultaneous zonal ones.

4.11.4. Total revenues

In Figure 4.76 the total value of remuneration for modelled services is reported. For the first four simulations, where constraint on full delivery of energy requested is imposed, earnings in case of *dual pricing* or *single pricing* algorithm application are differentiated. Regarding the remaining simulations instead, since no unbalances are generated there is only one corresponding value.

From the chart it is clear how primary frequency regulation represent the most relevant source of value, in fact simulations providing only tertiary reserve are limited to really low earning values or even go so far as to record a loss related to penalties due to imbalances.

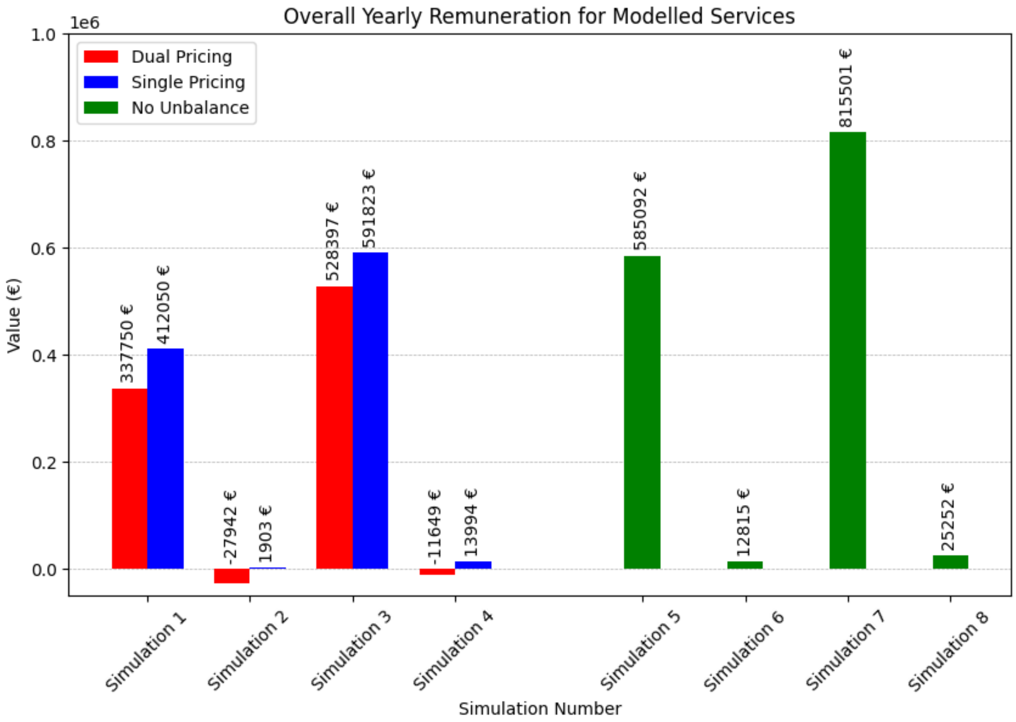


Figure 4.76: Overall yearly revenues for modelled services

To better understand the magnitude of the earnings it is interesting to normalise revenues on the number of vehicles participating to the services provision. Since the simulation is based on recorded trips and not vehicles it is necessary to find a coefficient to correlate travels with vehicles. From the mobility study of*Regione Lombardia* [40], source of employed data, emerges that the average number of trips in a day performed by a single vehicle is 2.54. So it is possible to divide the number of identified *electric travels* (197'075) by this coefficient to estimate the number of EVs considered in the simulation that results to be 77'589.

In the most remunerative scenario simulated, the one with impacted charge, flexibility offered in both directions and with the application of the *bands enhancement* algorithm, the yearly revenue per vehicle is slightly above €10.5/year. This number is clearly not enough to motivate final users to participate in such a scheme, leading to the necessity of an intervention by the ruler to enable provision of modelled services by an aggregate of EVs. While the financial remuneration is not satisfactory it is important to note that the impact on energy delivery is very limited and almost negligible for the most remunerative service that is primary frequency regulation.

4.12. Spatial analysis of the aggregate

By integrating the findings of the analysis with geospatial data, it is possible to assess the geographical distribution of the total available capacity for a service across the Lombardy region. In Figure 4.77 and Figure 4.78 are displayed the values of the available primary regulation band per each single primary substation.

The left-hand side diagrams illustrate the values for the pool following the implementation of the *"primary bands enhancement"* algorithm using the *"impacted charge"* methodology. Conversely, the right-hand side diagrams show the equivalent values without the application of bands enhancement. The images correspond to the first five minutes time window belonging to hours 5 and 20, respectively, and each employs the designated scale, located at the center of each figure, to emphasize the most significant locations and to distinctly show the effect of the application of the *"primary bands enhancement"* algorithm.

As highlighted in Section section 4.1, 5 a.m. is identified as a critical time in terms of vehicle availability. The disparity between the two plots is pronounced; the left plot shows values reaching as high as 85 kW, whereas the right plot indicates that no primary substation achieves even 5 kW of available primary regulation band.

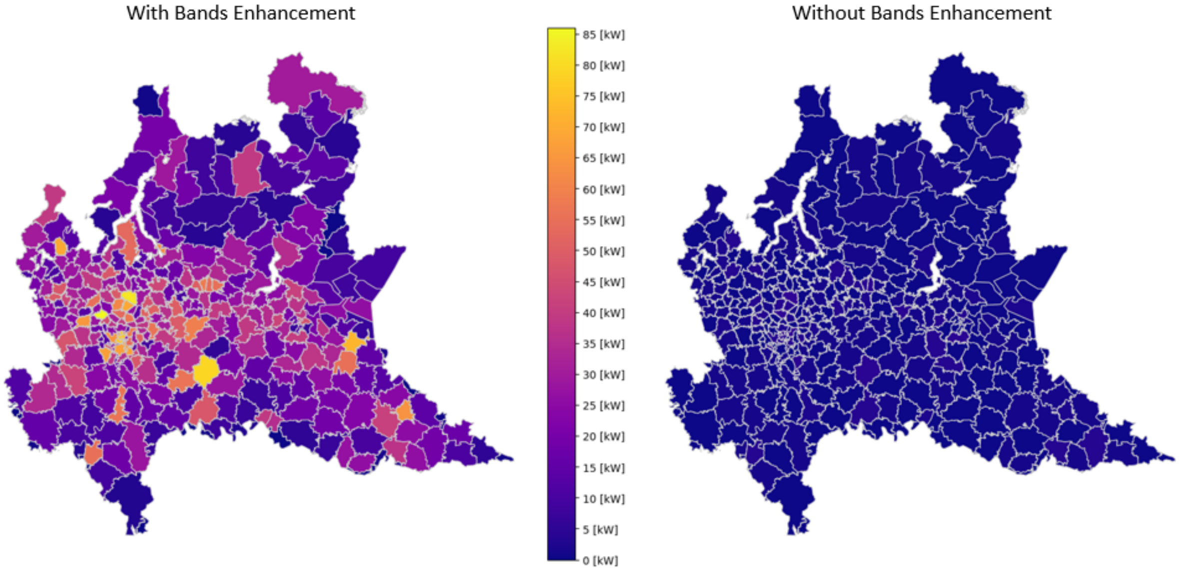


Figure 4.77: Primary band spatial distribution at 5 a.m.

Conversely at 8 p.m., a peak time for charging processes in the evening, the *"bands* *enhancement"* algorithm moves travels forward to cover for the valleys taking place in the morning, so the values are reduced from up to 150 kW to slightly more than 100 kW.

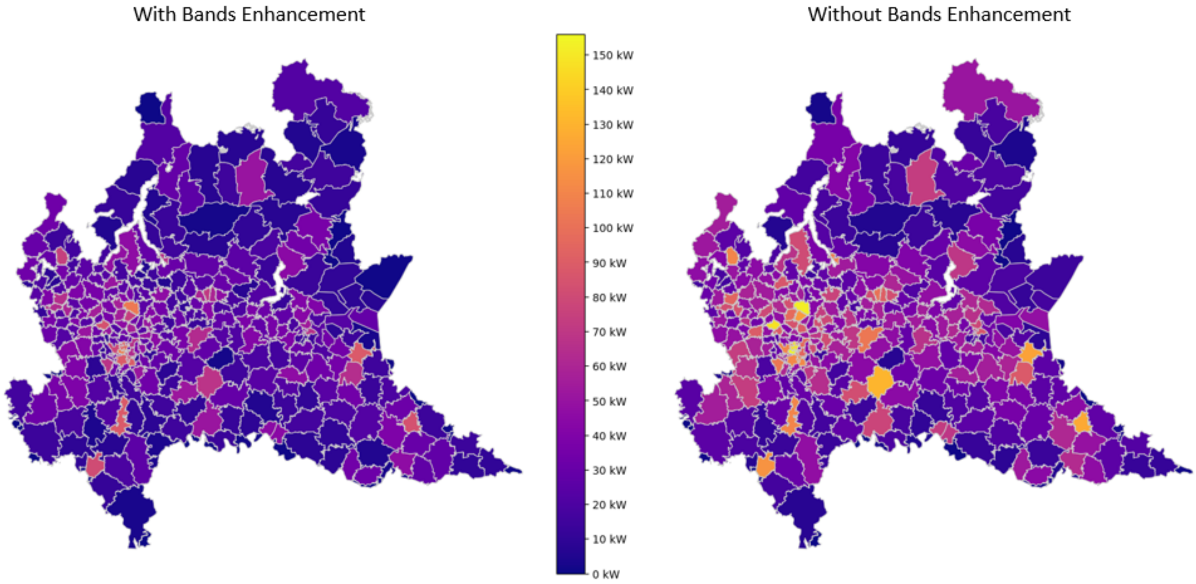
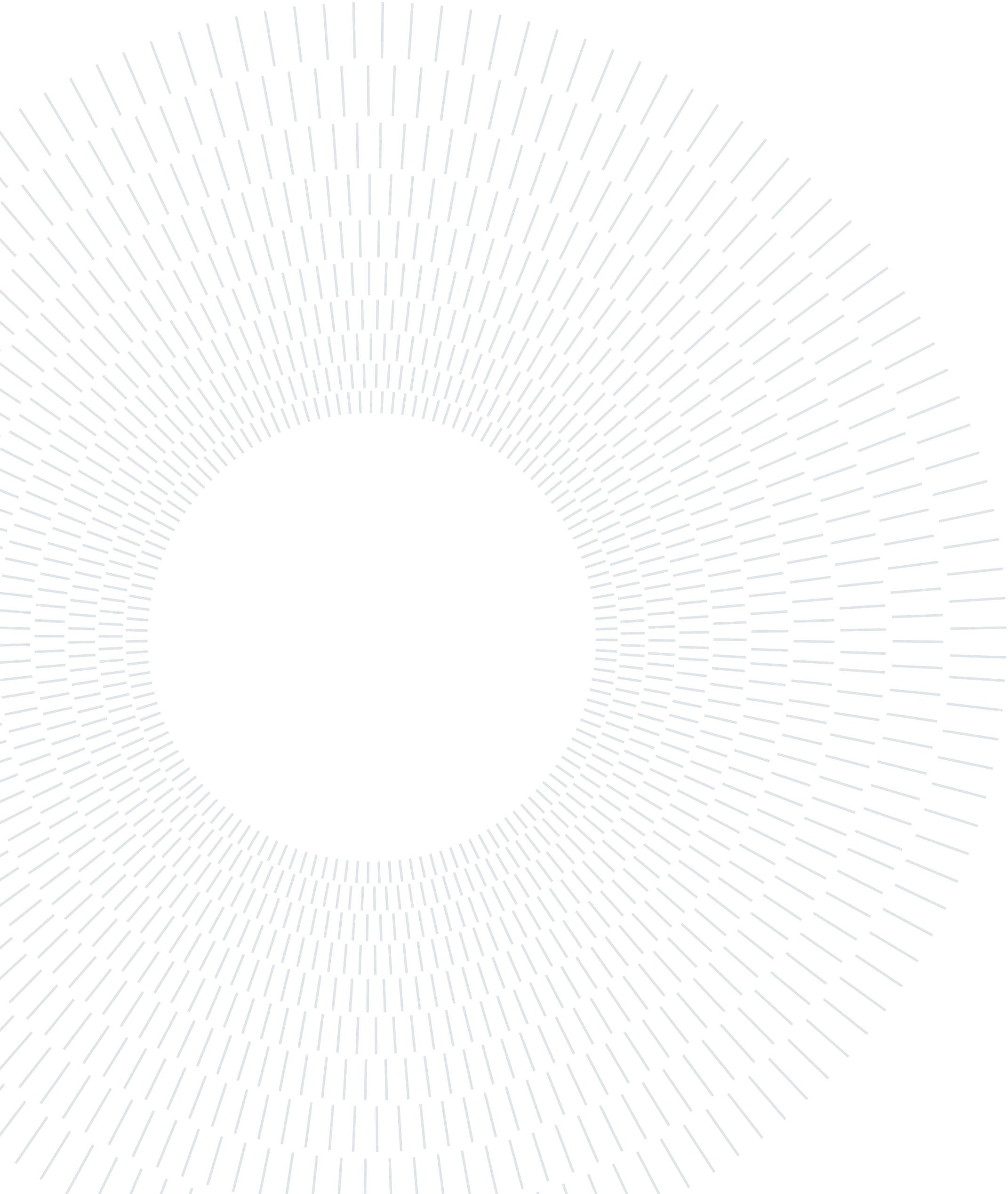


Figure 4.78: Primary band spatial distribution at 8 p.m.

In all figures presented substations serving urban areas are the ones that show the highest potential in terms of primary frequency regulation. This is clearly attributable to the higher number of vehicles charging in those areas. These substations are the ones that would be stressed the most by uncontrolled charge so the ones that would benefit the most from the application of smart charging logics.



5 | Conclusions and future work

5.1. Conclusions

The thesis was devoted to investigating the potential in grid services provision from a pool of EVs, starting from real data on trips taking place in the whole Lombardy region in a typical day. The described approach is structured to be capable of performing the same analysis on grid services potential starting from analogue data (an OD matrix) referenced to another geographical area.

What stand out from the numerical results are the power values of the flexibility bands, both in the provision of primary frequency regulation and tertiary reserve. When the penetration of EVs will reach a significant share it will be essential to be able to control charging processes: on the one hand to avoid overloads on distribution and transmission grid, on the other hand to be able to exploit the decentralised energy storage potential for contributing to ancillary services provision. In a scenario where the use of unpredictable renewable energy sources is expected to grow, leading to a higher demand for ancillary services, the effective management of electric vehicle (EV) charging processes could emerge as a highly strategic asset.

To ease EVs participation in the ancillary services market what results from this study is that the current selection logic for tertiary reserve provision strongly penalises a resource with limited power like the modelled aggregate. The suggestion for the ruler is so to reduce technical entrance barriers and keep in consideration distributed storage resources when technically feasible, also given the economically competitive prices they can offer having no marginal cost for this service provision. As it stands out from the analysis performed in subsection 4.11.3, a single pricing algorithm logic in the evaluation of unbalances provoked by the aggregates can be beneficial from the economical point of view, and encourage the participation of EVs' aggregates to the ancillary services market.

Results on remuneration presented in subsection 4.11.4 appear to be too modest to solely motivate an EV owner's participation in such a scheme, assessing to a value slightly higher than €10 per year per vehicle. Therefore, to harness the capabilities of an EV aggregate as a distributed storage resource, a dedicated regulatory framework should be implemented to norm EVs' participation to ancillary services provision. Additionally, implementing these services requires updating the infrastructure of charging stations. Each charging point must have the capability for real-time, secure communication with the entity responsible for overseeing the collective system.

The most relevant limit of the proposed methodology arise from the challenge of simulating the behaviour of single vehicles during the day, including its state of charge and potential charging locations. Unfortunately, the data set available did not enable the tracking of individual car movements throughout the day, precluding a more granular depiction of each vehicle's capability to contribute to grid services.

5.2. Future improvements

5.2.1. Trip chains construction

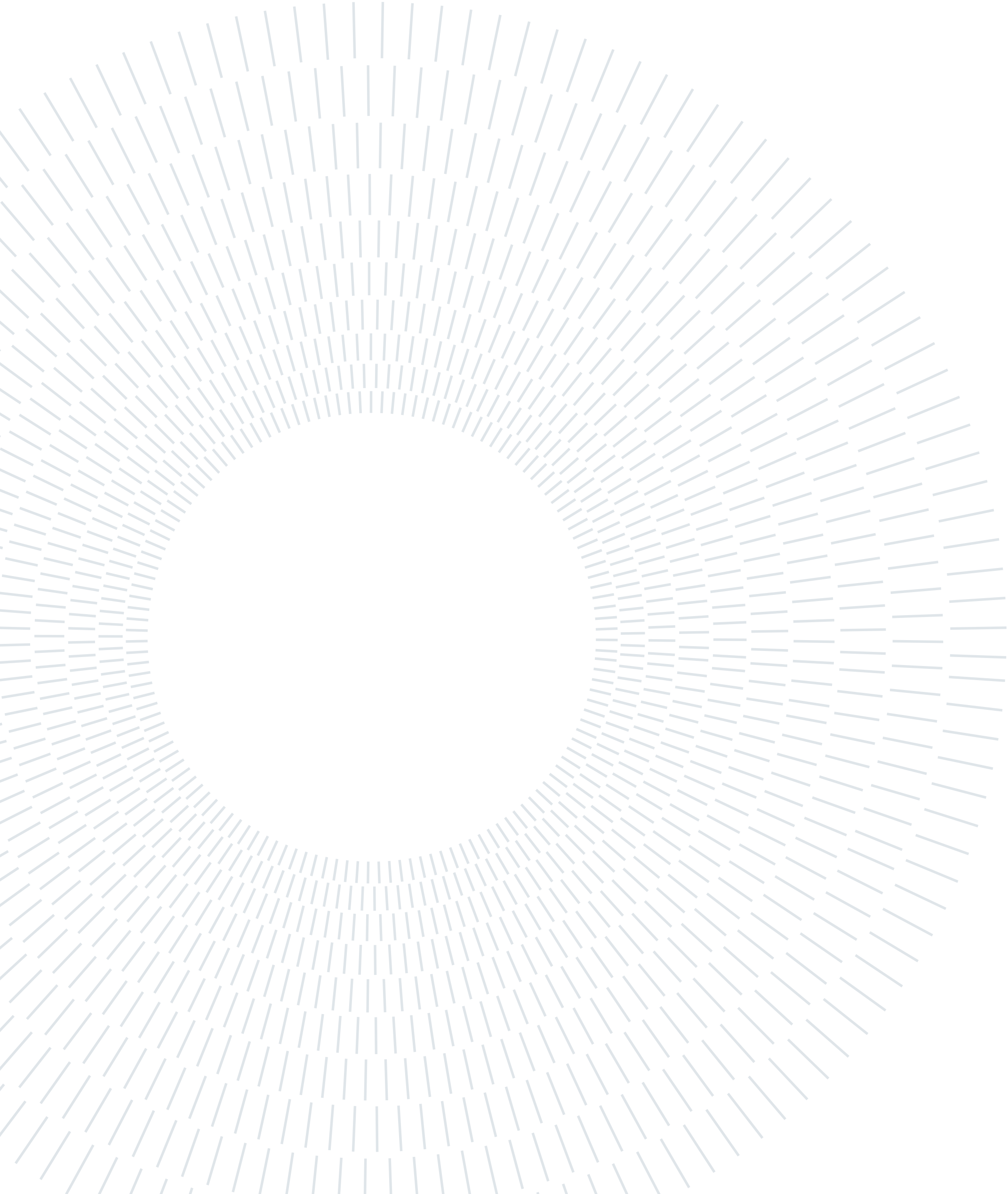
One of the most relevant improvements that could be implemented to increase the accuracy of the presented work is the creation of a consistent methodology to generate *"trip chains"* that represent the daily behavior of drivers.

Unfortunately, the available data set used for the presented model (the Origin-Destination matrix published by *Regione Lombardia*), did not allow to adopt this approach without adding strongly impacting assumptions. In fact, the discrepancy between incoming and leaving travels from each area is relevant in terms of value and not uniform in terms of "sign". For this reason building coherent trip chains with travels with different goal and same starting and end point would mean discard a large number of trips. This could lead to a significant deviation from reality due to the randomly coupled trips.

To effectively implement *"trip chains"* in the analysis, a differently structured data set is needed in order to limit the additional assumptions.

5.2.2. Charging points location

While studying the interactions between mobility and the grid it is crucial to properly model the interface between these two *"worlds"* that is the charging infrastructure. Despite being reasonable, the assumption adopted in the presented study, of having a number of charging points proportional to the EV adoption of a determined area could be an oversimplification. For this reason an interesting possible future update could be the integration of tools for the optimal allocation of charging points. *Scarica.isea* [49] could represent a viable option: it integrates data on population and workplaces locations to find optimal siting for new chargers. Despite simplifications due to the lack of specific knowledge about uniqueness of each area, if integrated with real world data on the specific case, this tool could represent a significant upgrade in the accuracy of the model.



Bibliography

[1] International Energy Agency. CO2 emissions by sector. Technical report, IEA, 2023. Accessed on October 06, 2023.

[2] European Environment Agency. CO2 emissions in transport sector. Technical report, EEA, 2019. Accessed on October 06, 2023.

[3] Motorlease. Types of hybrid vehicles. Technical report, Motorlease, 2020. Accessed on October 06, 2023.

[4] EVgo. Types of electric vehicles. Technical report, EVgo, 2023. Accessed on October 06, 2023.

[5] ACEA. Electrified vehicles maeket shares. Technical report, ACEA, 2023. Accessed on October 06, 2023.

[6] European Environment Agency. Registration of new electric vehicles in Europe. Technical report, EEA, 2022. Accessed on October 06, 2023.

[7] ACEA. Registration of new electric vehicles in Europe. Technical report, ACEA, 2023. Accessed on October 06, 2023.

[8] European Commission. EV market shares in Europe. Technical report, EC, 2022. Accessed on October 06, 2023.

[9] International Energy Agency. Grid integration of electric vehicles manual. Technical report, IEA, 2022. Accessed on October 06, 2023.

[10] Nuvve. V1G and V2G Definition. Technical report, Nuvve, 2023. Accessed on November 06, 2023.

[11] European Environment Agency. Report on LCA of electric vehicles. Technical report, EEA, 2018. Accessed on October 06, 2023.

[12] Elecdrive. EU charging points distribution. Technical report, Elecdrive, 2023. Accessed on October 06, 2023.

[13] Virta. Cmart charging overview. Technical report, Virta, 2023. Accessed on October 06, 2023.

[14] Windeurope. EU wind energy outlook. Technical report, Windeurope, 2017. Accessed on October 06, 2023.

[15] McKinsey. EUphotovoltaic outlook. Technical report, McKinsey, 2022. Accessed on October 06, 2023.

[16] EU. European Solar Strategy. Technical report, EU, 2023. Accessed on November 06, 2023.

[17] International Energy Agency. Curtailment. Technical report, IEA, 2023. Accessed on October 06, 2023.

[18] Piergiorgio Alotto, Massimo Guarnieri, and Federico Moro. Redox flow batteries for the storage of renewable energy: A review. *Renewable and Sustainable Energy Reviews*, 29:325–335, 2014.

[19] Arthur D. Little. Smart Charging Protocols. Technical report, Arthur D. Little, 2020. Accessed on November 06, 2023.

[20] Johannes Kester, Lance Noel, Xiao Lin, Gerardo Zarazua de Rubens, and Benjamin K. Sovacool. The coproduction of electric mobility: Selectivity, conformity and fragmentation in the sociotechnical acceptance of vehicle-to-grid (v2g) standards. *Journal of Cleaner Production*, 207:400–410, 2019.

[21] Oracle. ICCP Protocol Description. Technical report, Oracle, 2023. Accessed on November 06, 2023.

[22] Vector. Low Lelvel Communication Protocols. Technical report, Vector, 2020. Accessed on November 06, 2023.

[23] Mart van der Kam and Rudi Bekkers. Mobility in the smart grid: Roaming protocols for ev charging. *IEEE Transactions on Smart Grid*, 14(1):810–822, 2023.

[24] Juan Ignacio Guerrero Alonso, Enrique Personal, Sebastián García, Antonio Parejo, Mansueto Rossi, Antonio García, Federico Delfino, Ricardo Pérez, and Carlos León. Flexibility services based on openadr protocol for dso level. *Sensors*, 20(21), 2020.

[25] Néstor Rodríguez Pérez, Javier Matanza Domingo, Gregorio López López, José Pablo Chaves Ávila, Ferdinando Bosco, Vincenzo Croce, Kalle Kukk, Mathias Uslar, Carlos Madina, and Maider Santos-Mugica. Ict architectures for tso-dso coordina-

tion and data exchange: A european perspective. *IEEE Transactions on Smart Grid*, 14(2):1300–1312, 2023.

[26] Terna. Annex 6 to UVAM regulation. Technical report, Terna, 2023. Accessed on October 06, 2023.

[27] Gestore Mercati Elettrici. Italian electricity market description. Technical report, GME, 2023. Accessed on October 06, 2023.

[28] National Renewable Energy Laboratory. Typologies of grid services. Technical report, NREL, 2019. Accessed on October 06, 2023.

[29] EEPower. Frequency regulation. Technical report, EEPower, 2020. Accessed on October 06, 2023.

[30] GridSingularity. Balancing market structure. Technical report, GridSingularity, 2023. Accessed on October 06, 2023.

[31] Terna. Capter 4 to Grid Code. Technical report, Terna, 2023. Accessed on October 06, 2023.

[32] EnelX. Interruptibility Service Description. Technical report, Enel, 2023. Accessed on November 06, 2023.

[33] Terna. UVAM regulation. Technical report, Terna, 2023. Accessed on October 06, 2023.

[34] Terna. Annex 2 to UVAM regulation. Technical report, Terna, 2023. Accessed on October 06, 2023.

[35] Terna. Annex 22 to UVAM regulation. Technical report, Terna, 2023. Accessed on October 06, 2023.

[36] Terna. Annex 23 to UVAM regulation. Technical report, Terna, 2023. Accessed on October 06, 2023.

[37] Yujie Sheng, Yanxi Lin, Hongtai Zeng, Yang Yu, Qinglai Guo, and Shiwei Xie. Emission-concerned coordinated dispatching of electrified autonomous mobility-on-demand system and power system incorporating heterogeneous spatiotemporal scales. *Sustainable Cities and Society*, 98:104755, 2023.

[38] Zhiyan Yi, Bingkun Chen, Xiaoyue Cathy Liu, Ran Wei, Jianli Chen, and Zhuo Chen. An agent-based modeling approach for public charging demand estimation and charging station location optimization at urban scale. *Computers, Environment and Urban Systems*, 101:101949, 2023.

[39] Yunfei Mu, Jianzhong Wu, Nick Jenkins, Hongjie Jia, and Chengshan Wang. A spatial–temporal model for grid impact analysis of plug-in electric vehicles. *Applied Energy*, 114:456–465, 2014.

[40] Regione Lombardia. Origin and Destination matrix. Technical report, Regione Lombardia, 2014. Accessed on October 06, 2023.

[41] Yousefi Ghaffar. Methodologies for predicting the impact of electric mobility in distribution networks through georefrenced data. Master's thesis, Politecnico di Milano, https://hdl.handle.net/10589/211366, 2023.

[42] ANFIA. Distribution of EVs. Technical report, ANFIA, 2023. Accessed on November 06, 2023.

[43] Virta. EV average consumption estimation. Technical report, Virta, 2022. Accessed on October 06, 2023.

[44] Filippo Bovera, Alessandro Blaco, Giuliano Rancilio, and Maurizio Delfanti. Assessing the accuracy of different machine learning classification algorithms in forecasting results of italian ancillary services market. 2019.

[45] F. Bovera M. Spiller, G. Rancilio and M. Merlo. *Opportunities for DERs in Ancillary Services Markets: analysis and deployment strategies in a national framework*. 18th International Conference on the European Energy Market (EEM), 2022.

[46] insideevs. Public charging points in Lombardy. Technical report, insideevs, 2023. Accessed on October 06, 2023.

[47] REGELLEISTUNG.NET. Prices For Primary Freqency Control. Technical report, REGELLEISTUNG.NET, 2023. Accessed on November 06, 2023.

[48] GME. Prices of MGP. Technical report, GME, 2023. Accessed on November 06, 2023.

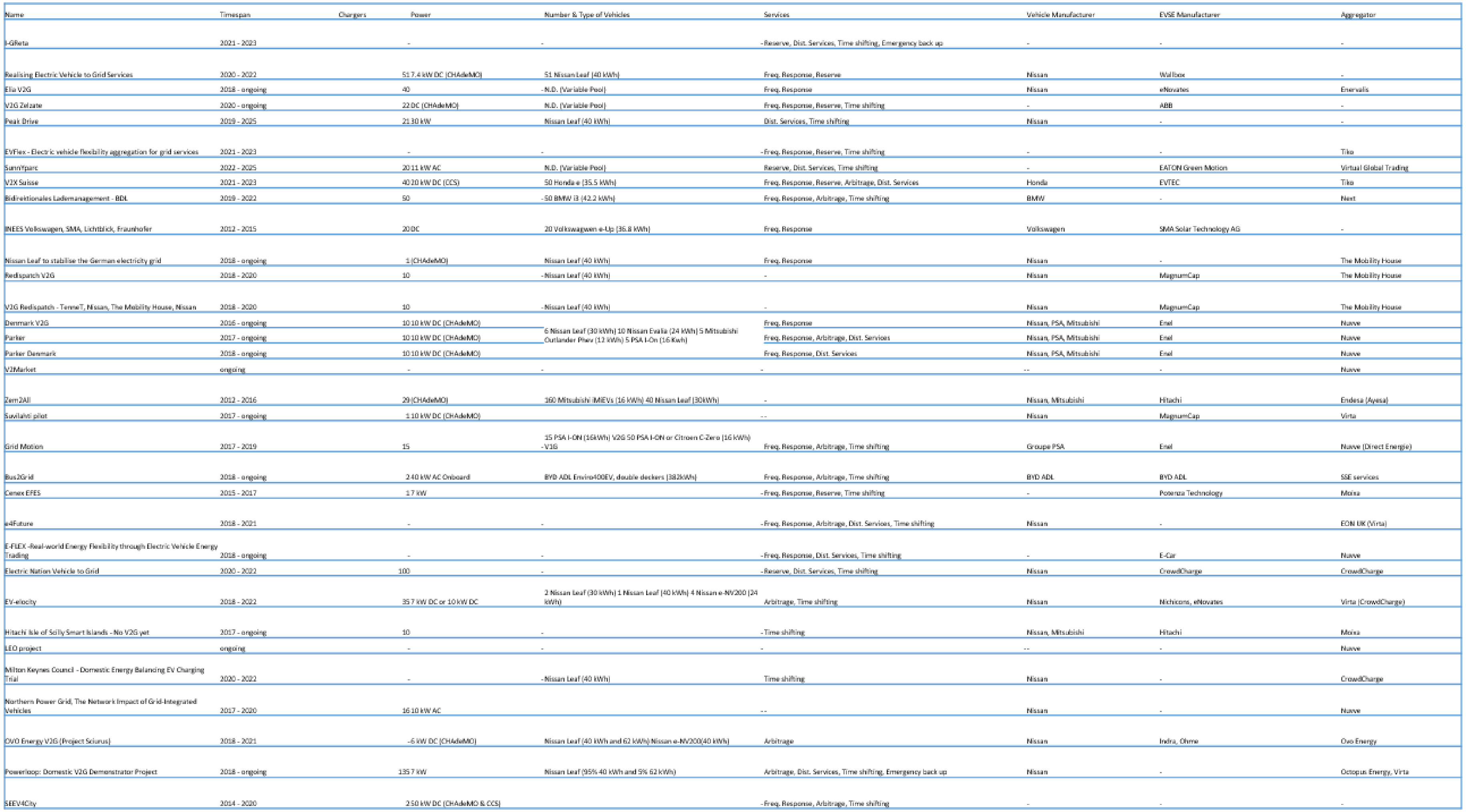
[49] RWTH Aachen. Charging Points Loction. Technical report, RWTH Aachen, 2023. Accessed on November 06, 2023.

[50] Terna. Remuneration for Interruptibility. Technical report, Terna, 2023. Accessed on November 06, 2023.

A | Appendix A

A.1. Research on V1G and V2G pilot projects

In Figure A.1 and Figure A.2 it is reported an overview of currently most relevant pilot projects on smart charging topics.

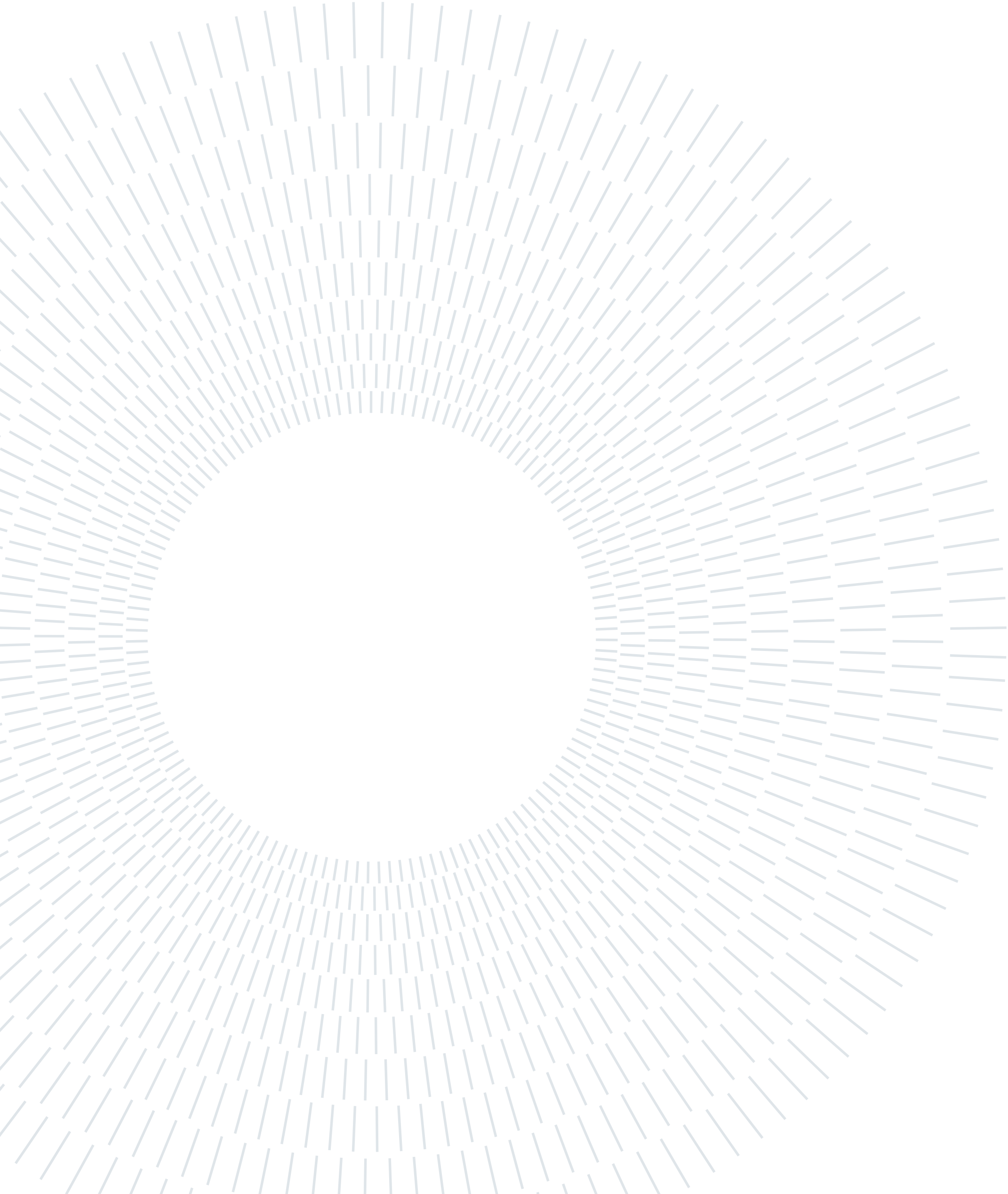


Name	Timespan	Chargers	Power	Number & Type of Vehicles	Services	Vehicle Manufacturer	EVSE Manufacturer	Aggregator
I-GReta	2021 - 2023		-	-	-Reserve, Dist. Services, Time shifting, Emergency back up	-	-	-
Realising Electric Vehicle to Grid Services	2020 - 2022	51	7.4 kW DC (CHAdeMO)	51 Nissan Leaf (40 kWh)	Freq. Response, Reserve	Nissan	Wallbox	-
Elia V2G	2018 - ongoing	40		-N.D. (Variable Pool)	Freq. Response	Nissan	eNovates	Enervalis
V2G Zelzate	2020 - ongoing	22	DC (CHAdeMO)	N.D. (Variable Pool)	Freq. Response, Reserve, Time shifting	-	ABB	-
Peak Drive	2019 - 2025	21	30 kW	Nissan Leaf (40 kWh)	Dist. Services, Time shifting	Nissan	-	-
EVFlex - Electric vehicle flexibility aggregation for grid services	2021 - 2023		-	-	-Freq. Response, Reserve, Time shifting	-	-	Tiko
SunnYparc	2022 - 2025	20	11 kW AC	N.D. (Variable Pool)	Reserve, Dist. Services, Time shifting	-	EATON Green Motion	Virtual Global Trading
V2X Suisse	2021 - 2023	40	20 kW DC (CCS)	50 Honda e (35.5 kWh)	Freq. Response, Reserve, Arbitrage, Dist. Services	Honda	EVTEC	Tiko
Bidirektionales Lademanagement - BDL	2019 - 2022	50		-50 BMW i3 (42.2 kWh)	Freq. Response, Arbitrage, Time shifting	BMW	-	Next
INEES Volkswagen, SMA, Lichtblick, Fraunhofer	2012 - 2015	20	DC	20 Volkswagen e-Up (36.8 kWh)	Freq. Response	Volkswagen	SMA Solar Technology AG	-
Nissan Leaf to stabilise the German electricity grid	2018 - ongoing	1	(CHAdeMO)	Nissan Leaf (40 kWh)	Freq. Response	Nissan	-	The Mobility House
Redispatch V2G	2018 - 2020	10		-Nissan Leaf (40 kWh)	-	Nissan	MagnumCap	The Mobility House
V2G Redispatch - TenneT, Nissan, The Mobility House, Nissan	2018 - 2020	10		-Nissan Leaf (40 kWh)	-	Nissan	MagnumCap	The Mobility House
Denmark V2G	2016 - ongoing	10	10 kW DC (CHAdeMO)	6 Nissan Leaf (30 kWh) 10 Nissan Evalia (24 kWh) 5 Mitsubishi Outlander Phev (12 kWh) 5 PSA I-On (16 Kwh)	Freq. Response	Nissan, PSA, Mitsubishi	Enel	Nuvve
Parker	2017 - ongoing	10	10 kW DC (CHAdeMO)		Freq. Response, Arbitrage, Dist. Services	Nissan, PSA, Mitsubishi	Enel	Nuvve
Parker Denmark	2018 - ongoing	10	10 kW DC (CHAdeMO)		Freq. Response, Dist. Services	Nissan, PSA, Mitsubishi	Enel	Nuvve
V2Market	ongoing		-	-	-	--	-	Nuvve
Zem2All	2012 - 2016	29	(CHAdeMO)	160 Mitsubishi iMiEVs (16 kWh) 40 Nissan Leaf (30kWh)	-	Nissan, Mitsubishi	Hitachi	Endesa (Ayesa)
Suvilahti pilot	2017 - ongoing	1	10 kW DC (CHAdeMO)		--	Nissan	MagnumCap	Virta
Grid Motion	2017 - 2019	15		15 PSA I-ON (16kWh) V2G 50 PSA I-ON or Citroen C-Zero (16 kWh) -V1G	Freq. Response, Arbitrage, Time shifting	Groupe PSA	Enel	Nuvve (Direct Energie)
Bus2Grid	2018 - ongoing	2	40 kW AC Onboard	BYD ADL Enviro400EV, double deckers (382kWh)	Freq. Response, Arbitrage, Time shifting	BYD ADL	BYD ADL	SSE services
Cenex EFES	2015 - 2017	1	7 kW		-Freq. Response, Reserve, Time shifting	-	Potenza Technology	Moixa
e4Future	2018 - 2021		-	-	-Freq. Response, Arbitrage, Dist. Services, Time shifting	Nissan	-	EON UK (Virta)
E-FLEX -Real-world Energy Flexibility through Electric Vehicle Energy Trading	2018 - ongoing		-	-	-Freq. Response, Dist. Services, Time shifting	-	E-Car	Nuvve
Electric Nation Vehicle to Grid	2020 - 2022	100		-	-Reserve, Dist. Services, Time shifting	Nissan	CrowdCharge	CrowdCharge
EV-elocity	2018 - 2022	35	7 kW DC or 10 kW DC	2 Nissan Leaf (30 kWh) 1 Nissan Leaf (40 kWh) 4 Nissan e-NV200 (24 kWh)	Arbitrage, Time shifting	Nissan	Nichicons, eNovates	Virta (CrowdCharge)
Hitachi Isle of Scilly Smart Islands - No V2G yet	2017 - ongoing	10		-	-Time shifting	Nissan, Mitsubishi	Hitachi	Moixa
LEO project	ongoing		-	-	-	--	-	Nuvve
Milton Keynes Council - Domestic Energy Balancing EV Charging Trial	2020 - 2022		-	-Nissan Leaf (40 kWh)	Time shifting	Nissan	-	CrowdCharge
Northern Power Grid, The Network Impact of Grid-Integrated Vehicles	2017 - 2020	16	10 kW AC		--	Nissan	-	Nuvve
OVO Energy V2G (Project Sciurus)	2018 - 2021	-	6 kW DC (CHAdeMO)	Nissan Leaf (40 kWh and 62 kWh) Nissan e-NV200(40 kWh)	Arbitrage	Nissan	Indra, Ohme	Ovo Energy
Powerloop: Domestic V2G Demonstrator Project	2018 - ongoing	135	7 kW	Nissan Leaf (95% 40 kWh and 5% 62 kWh)	Arbitrage, Dist. Services, Time shifting, Emergency back up	Nissan	-	Octopus Energy, Virta
SEEV4City	2014 - 2020	2	50 kW DC (CHAdeMO & CCS)		-Freq. Response, Arbitrage, Time shifting	-	-	-

Figure A.1: Summary of most relevant info on Pilot Projects on V1G/V2G

SMARTHUBS Demonstrator	2018 - 2022	-	-	--	Honda	-	Flexitricity
UK Vehicle-2-Grid (V2G)	2016 - ongoing	-	-	--	Nissan	-	Enel
V2GO	2018 - ongoing	-	-	-Freq. Response, Arbitrage, Time shifting	-	-	Kraken Flex
V2X By Marubeni	2021 - ongoing	-	-	-Freq. Response, Arbitrage, Dist. Services, Time shifting	-	-	Virta
VIGIL (Vehicle to Grid Intelligent control)	2020 - ongoing	-	-	-Reserve, Dist. Services, Time shifting	-	-	-
BloRin	2019 - ongoing	-	-	-Freq. Response, Time shifting	-	-	Blorin
E-mobility Lab	2021 - ongoing	-	-	-Freq. Response, Reserve, Time shifting	-	-	-
Fiat-Chrysler V2G (Italy)	2023 - 2027	6450 kW	Fiat 500e (24 kWh)	-	Fiat-Chrysler	-	Engie EPS
Genoa pilot	2017 - ongoing	-	-	--	Nissan	-	Enel
METI project	2018-2021	-	-	-	--	-	Nuvve
M-tech Labo	2010 - 2013	53 kW	5 Mitsubishi iMiEVs (16 kWh)	Time shifting, Emergency back up	Mitsubishi	Mitsubishi Electric	-
Toyota Tsuho / Chubu Electric / Nuvve	2018 - 2022	-	-	--	Toyota	-	Nuvve
V2G Aggregator project - Mitsubishi	2018 - unknown	-	-	--	Mitsubishi	Hitachi	TEPCO
KEPCO, Hyundai	2012 - ongoing	-	-	--	Hyundai	-	-
City-Zen Smart City	2014 - 2019	410 kW AC (CHAdeMO)		-Arbitrage, Dist. Services	Mitsubishi	-	Enervalis
FlexGrid	2018 - 2022	-	-	-Freq. Response, Time shifting, Emergency back up	-	-	-
NewMotion V2G	2016 - 2018	10 10 kW	Mitsubishi Outlander Phev (12 kWh)	Freq. Response	Mitsubishi	Enel (NewMotion, Shell Recharge)	Nuvve
Powerparking	2017 - 2022	1 10 kW DC (CHAdeMO)	Nissan Leaf (30 kWh)	Time shifting	Nissan	-	-
Share the Sun / Deelkezon Project	2019 - 2021	-	-Nissan Leaf (40 kWh or 62 kWh)	Freq. Response, Dist. Services, Time shifting	Nissan	-	-
Smart Solar Charging	2015 - ongoing	-	-Renault Zoe (52kWh)	Dist. Services, Time shifting	Renault	Siers Group	-
Solar-powered bidirectional EV charging station	2015 - 2017	1 150 kW DC (CHAdeMO & CCS)		-Time shifting	Nissan	PRE	Last Mile Solutions
Utrecht V2G charge hubs (We Drive Solar)	2018 - ongoing	-	Renault Zoe (52 kWh) Hyundai Ioniq 5 (72.6 kWh) Hyunday Kona EV -(64 kWh) Tesla Model 3 (60 kWh)	Arbitrage	Renault, Tesla, Hyundai	-	WeDriveSolar
V2G @ home	2021 - ongoing	1 7.4 kW DC (CHAdeMO)	Nissan Leaf e+ (56 kWh)	Time shifting, Emergency back up	Nissan	Wallbox	-
V2G Liberty	2020 - ongoing	1 7.4 kW DC (CHAdeMO)	Nissan Leaf e+ (56 kWh)	Time shifting, Emergency back up	Nissan	Wallbox	-
V2G/V2B at the Johan Cruijff ArenA in Amsterdam	2019 - ongoing	1 10 kW DC	Nissan Leaf	Dist. Services, Emergency back up	Nissan	-	The Mobility House
EV Smart Charging Trial	2022 - 2024	-	-	-	--	Vector	Vector
Intelligent software from The Mobility House makes an entire island fossil free	2019 - ongoing	27.6 kW AC (CHAdeMO & CCS)	14 Renault Zoe (52 kWh) 6 Renault Kangoo (45 kWh)	Freq. Response, Dist. Services	Renault	dcbel	The Mobility House
Renault, the mobility house - V1G at present	2018 - 2020	27.6 kW AC (CHAdeMO & CCS)	14 Renault Zoe (52 kWh) 6 Renault Kangoo (45 kWh)	Time shifting	Renault	dcbel	The Mobility House
V2G Azores	2019 - 2022	10	-10 Nissan Leaf	Freq. Response, Arbitrage, Time shifting	Nissan	Magnum Cap	Nuvve
E-REGIO with Power2U and ÖBO	2018 - 2020	-	-	-Freq. Response, Arbitrage, Dist. Services, Time shifting	-	-	-
BlueBird School Bus V2G	2017 - ongoing	-60 kW DC	1 Micro Bird G5 (100kWh) and 1 Type D All American (150 kWh)	Freq. Response, Time shifting, Emergency back up	Blue Bird	Nuvve	Nuvve
Distribution System V2G for Improved Grid Stability for Reliability	2015 - 2018	-	-	-Dist. Services, Time shifting	Fiat-Chrysler	-	-
INVENT - UCSD / Nissan / Nuvve	2017 - 2020	50	-BMW i3 (42.2 kWh) Mitsubishi Outlander Phev (12 kWh) Nissan Leaf	Freq. Response, Dist. Services, Time shifting	BMW, Nissan, Mitsubishi	Nuvve	Nuvve
Massachusetts Electric School Bus Pilot	2015 - 2018	-19.2 kW	eLion Bus (104 kWh)	-	Lion Bus	Tesla, Clipper Creek	-
NREL Integrate / living lab	2017 - unknown	3	-Mini E (32.6 kWh)	-	TransPower Bus, BMW	Nuvve	Nuvve
SmartMAUI, Hawaii	2013 - 2016	13 45 kW DC (CHAdeMO)		-Time shifting	Nissan	Hitachi	Hitachi
US Air Force	2012 - unknown	13 15 kW DC (CHAdeMO)	Nissan Leaf (24 kWh)	Freq. Response, Reserve, Time shifting, Emergency back up	Nissan	Princeton Power Systems	-
uYllo eMobility Programme - Smart Grid EcoSystem for EV-Grid Interoperability	2018 - 2023	-	-BMW i3 (42.2 kWh) Nissan Leaf	Freq. Response, Dist. Services, Time shifting	Nissan	uYllo	Nuvve

Figure A.2: Summary of most relevant info on Pilot Projects on V1G/V2G



B | Appendix B

B.1. Interruptibility service remuneration

Establish revenues from interruptibility service is extremely challenging since the model is based on data regarding a typical working day and so it is hard to determine the actual load that can be disconnected at every time of the year. From Figure 4.14 it is clear how without the application of the *bands enhancement* algorithm the added load in the morning hours approaches zero so the available power for this service is negligible. Conversely after *bands enhancement* as it can be noted in Figure 4.31 the load that can be disconnected at any time of the day (the minimum of the added profile) approaches 40 MW.

Regarding remuneration assessment, in Terna's documentation [50] it is reported the fixed annual fee in €/MW, that in continental Italy is set to €105'000. Taking a large safety coefficient like 50% it is possible to estimate the yearly revenues from this service to assess to 2.1M€ for simulations with *bands enhancement* application.

Since it is hard to predict whenever an extreme event that requires the utilization of this kind of service happens, for the sake of the economic analysis no further variable remuneration based on the actual provision of the service is accounted.

B.2. Additional simulations

B.2.1. High acceptance scenario

This simulation aims to model a future scenario where flexibility from aggregates alike the one represented in this work is more relevant and competitive in TSO's choices. The average acceptance value for Tertiary reserve provision in this simulation is changed from around 5% to roughly 80%. In Figure B.1 it is evident how the number of calls for tertiary reserve provision is dramatically increased while in Figure B.1 it is depicted the response of the aggregate to the calls.

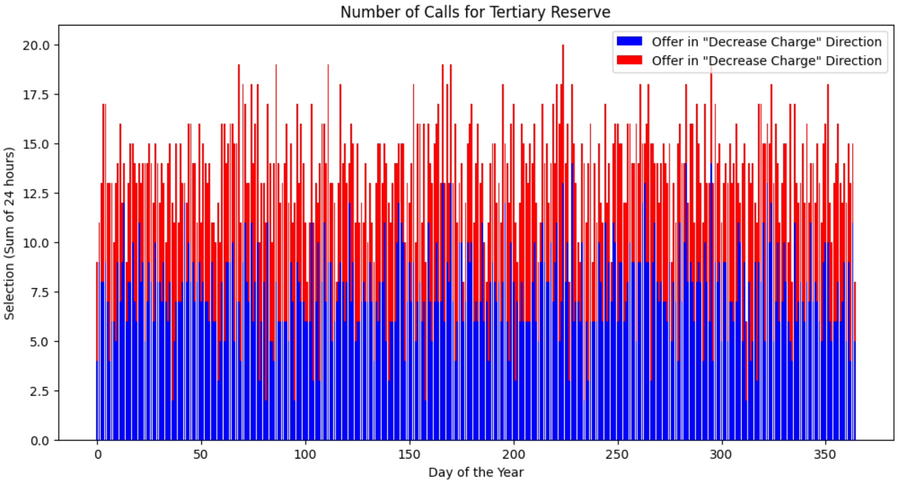


Figure B.1: Number of calls to tertiary reserve provision

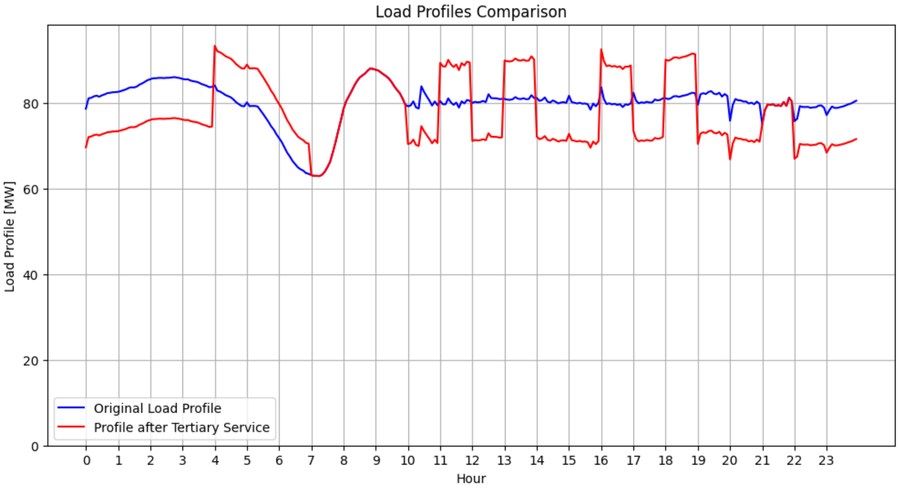


Figure B.2: Load profile before and after tertiary reserve provision

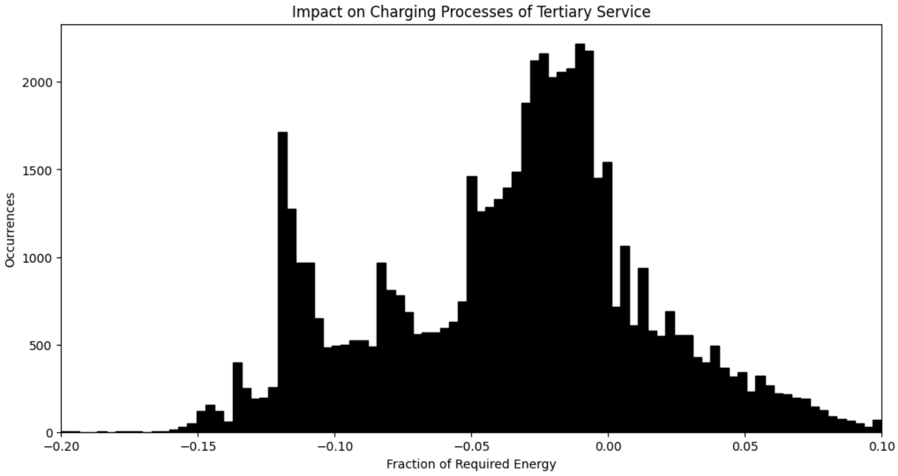


Figure B.3: Analysis of impact on EV charging processes

From Figure B.3 emerges the increased effort asked to each vehicle in the pool: a larger number of vehicles is impacted by the participation to tertiary reserve provision and the changes in charging stations' power output are more frequent. Despite the increased acceptance, even in the day with the highest number of calls, the deviation from original energy request for each travel is frequently limited between -5% and 0%.

Applying the same economical evaluation to this case, it emerges an higher potential in terms of revenues from tertiary reserve provision that assess to a value of €572'675, with with 2'791 calls in *"decrease charge"* and 2'312 calls in *"increase charge"*.

B.2.2. 30% EV penetration scenario

In this simulation it is reported the analysis on a future scenario where the penetration of EVs is 30%. With such a large share of electrified vehicles the impact on the grid of charging processes and consequently the potential application of smart charging logic is strongly enhanced. Together with the diffusion of EVs it is simulated also the simultaneous spread of public charging stations that for this scenario are assumed to be 150'000 in Lombardy (10 times the number assumed for the EV penetration scenario set at 2.5%). The simulation is run with the same settings as in section 4.9, so flexibility is offered in both directions, the *"primary Bands enhancement"* algorithm is applied and it is admitted a deviation from energy request by the user. Figure B.4 and Figure B.5 allow to quantify the impact on the grid of charging processes, which settles at an average additional load of 500 MW with peaks up to 1 GW.

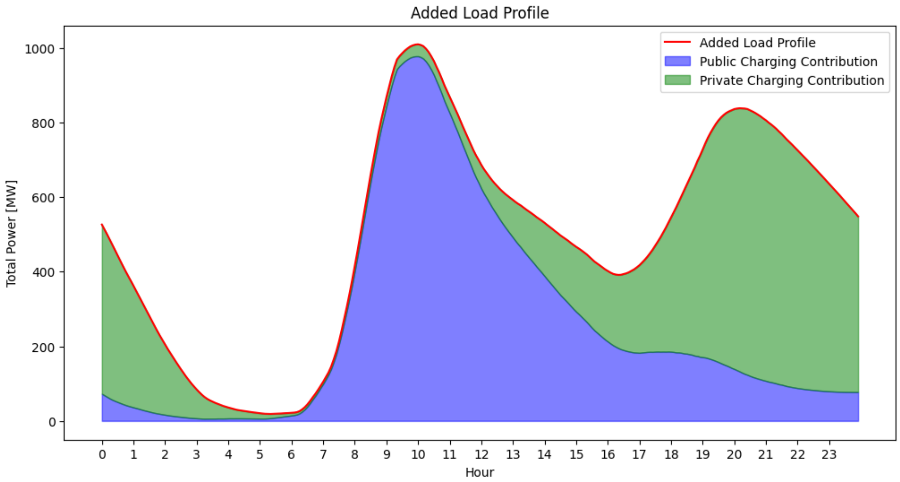


Figure B.4: Added load profile with contributions from public and domestic charging

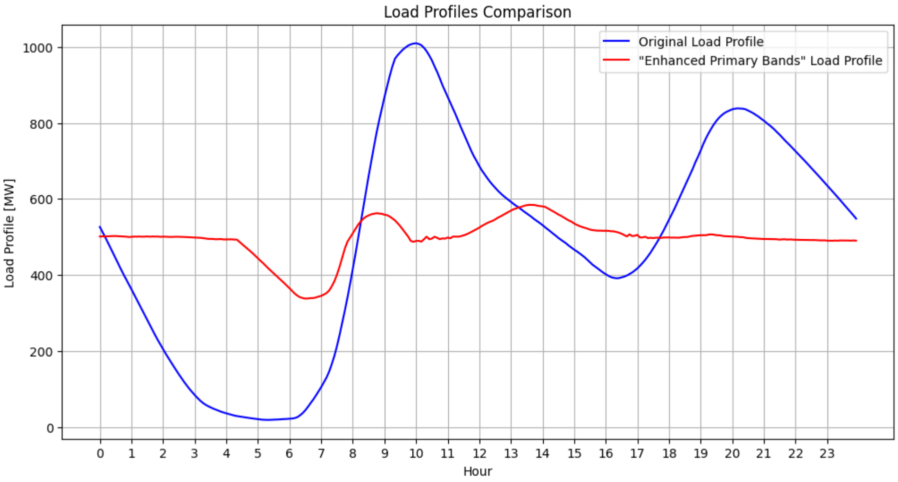


Figure B.5: Load profile before and after primary bands enhancement algorithm

Thanks to the application of the *"primary bands enhancement"* algorithm, the available band for the primary regulation service provision reaches a value that is comprehended between 35 and 70 MW, a significant amount at disposal of the TSO.

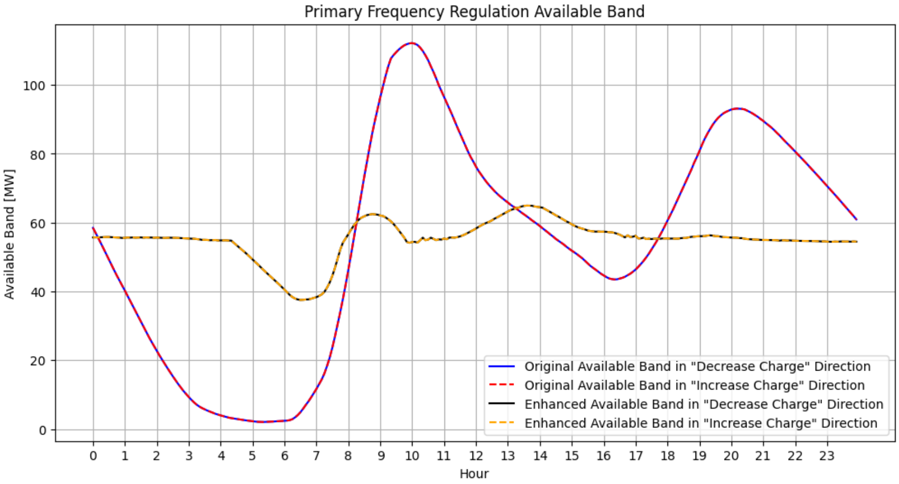


Figure B.6: Primary frequency regulation available bands

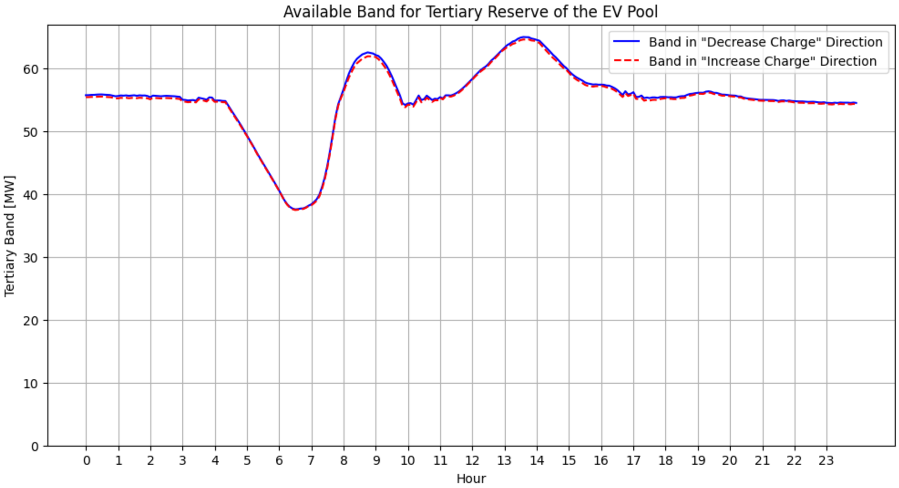
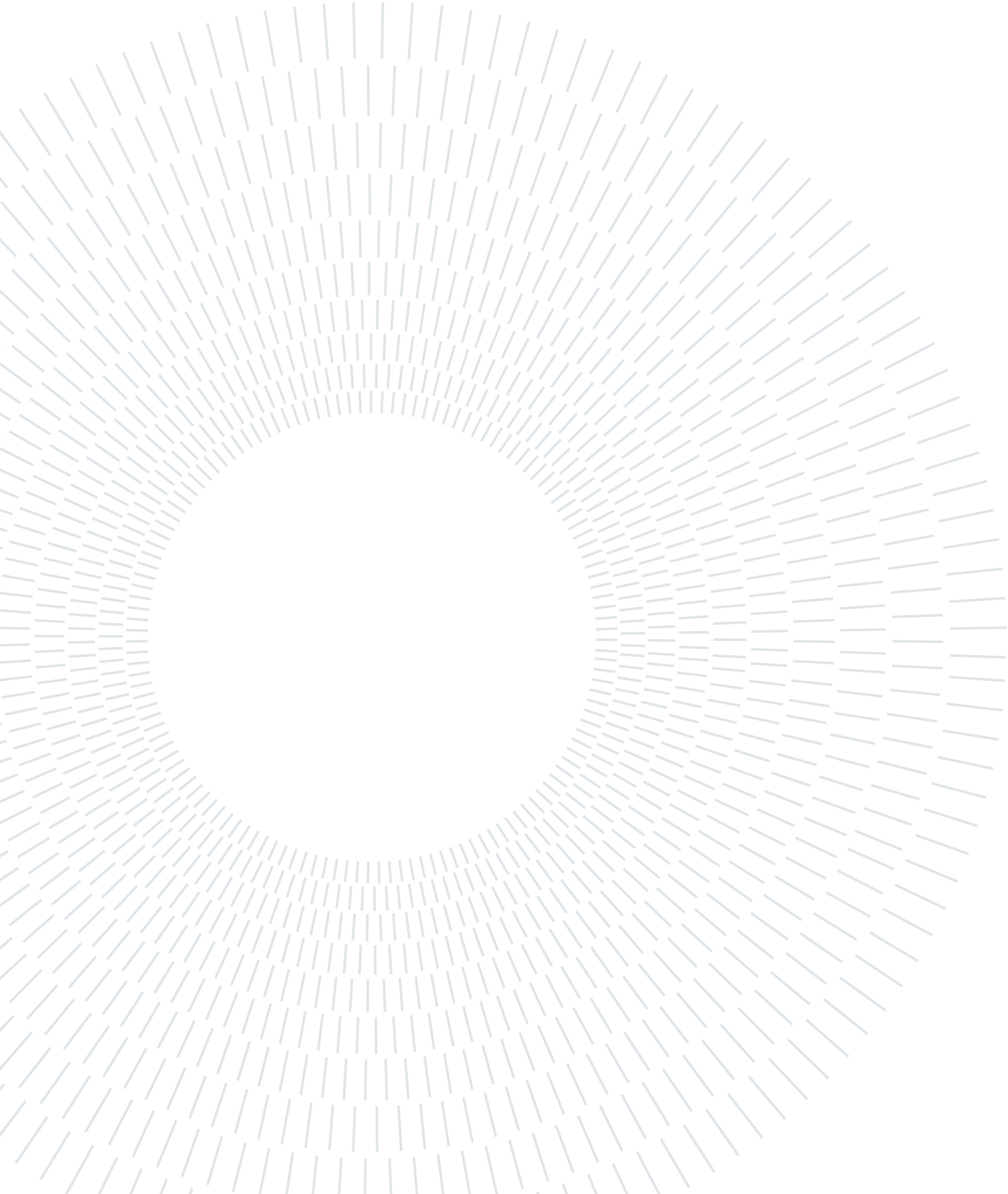
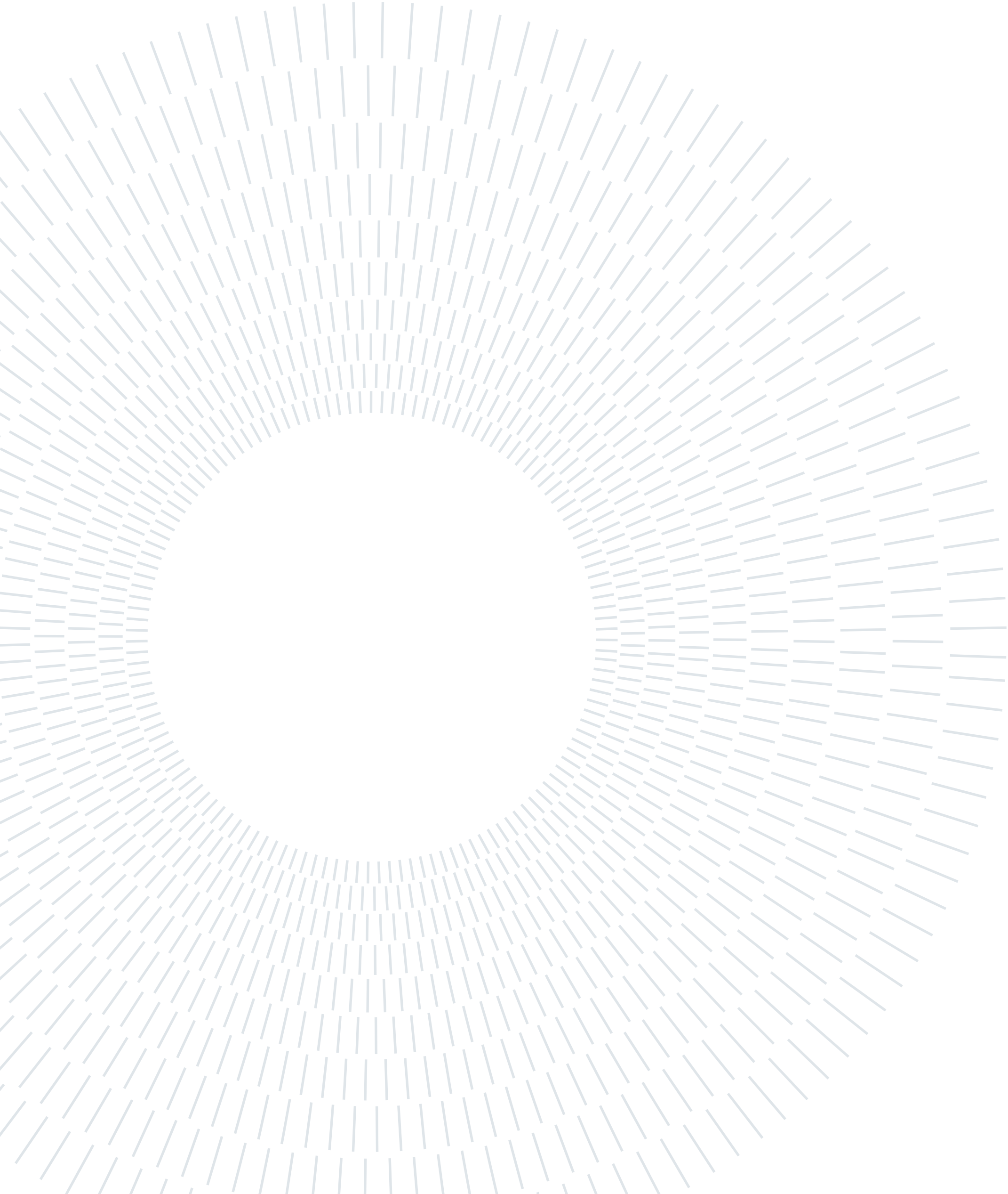


Figure B.7: Tertiary reserve service available bands



List of Figures

List of Tables



List of Abbreviations

Abbreviation	Description
EV	Electric vehicle
MHEV	Mild hybrid electric vehicle
FHEV	Full Hybrid electric vehicle
PHEV	Plug-in hybrid electric vehicle
EREV	Electric vehicle with range extender
BEV	Battery electric vehicle
RES	Renewable energy source
PV	Photovoltaic
LCA	Life cycle assessment
ICEV	Internal combustion engine vehicle
EVSE	Electric vehicle supply equipment
CPO	Charging point operator
EMSP	Electric mobility service provider
DSO	Distribution system Operator
TSO	Transmission system Operator
OCPP	Open charge point protocol
OCPI	Open charge point interface protocol
OCHP	Open clearing house protocol
OICP	Open inter charge protocol
eMIP	eMobility interoperation protocol
MGP	Mercato del giorno prima
MI	Intra - day market
MPEG	Mercato dei prodotti giornalieri
MSD	Mercato dei servizi di dispacciamento
UVAM	Unità virtuali abilitate miste

Acknowledgements

Voglio cominciare ringraziando di cuore il Professor Marco Merlo per avermi dato la possibilità di lavorare a questa ricerca e per il suo prezioso contibuto. Il professore è stato in questi mesi una guida straordinaria per conoscenze, esperienza, trasparenza, fiducia e passione nel suo lavoro. Lavorare con lui è stato per me un privilegio e un'occasione di grande crescita.

Un ringraziamento particolare va anche a Matteo Spiller, Corrado Maria Caminiti e Giuliano Rancilio per il grande supporto datomi lungo tutto il percorso della tesi e la loro straordinaria disponibilità. Sono davvero grato di aver lavorato con persone entusiaste e appassionate come voi. Grazie anche a Ghaffar Yousefi per aver condiviso con me il suo lavoro ed avermi aiutato con pazienza nelle fasi iniziali della tesi.

Nel mio percorso universitario credo che la cosa più bella e di maggior valore per me siano le persone che ho conosciuto. Ci tengo molto a ringraziare Livio, Chiara, Luca, Ivan, Federica, Claudio, Simone, Eleonora, Lara, Lorenzo, Tommaso, Mattéo, Elena, Matteo, Luca, Alessandro, Francesco, Vittorio, Sebastiano, Luca, Marco, Francesco, Eros e Lorenzo. Con alcuni di voi ho condiviso i primi anni di università, con altri lezioni, progetti e attività degli ultimi anni e con altri ancora il periodo della scrittura della tesi. Ciascuno di voi mi ha lasciato qualcosa, mi ha aiutato a crescere e ha condiviso con me momenti bellissimi. Provo grande stima e affetto per ciascuno di voi, grazie.

Voglio poi ringraziare i miei amici "storici" Matteo, Samuele, Francesco, Alessandro e Marco che ci sono sempre stati lungo questo percorso e su cui so di poter contare. Grazie anche a Stefano, Gloria, Silvia, Aurora, Silvia, Sofia, Leonardo, Alessandro e Edoardo per tutti i momenti di svago che abbiamo passato in questi anni. Un grazie speciale va a Christian, Lorenzo e Federico che insieme a Michele e Filippo hanno condiviso con me dei viaggi meravigliosi in questi ultimi due anni. Siete stati dei compagni di viaggio e degli amici straordinari.

Infine il grazie più importante di tutti va alla mia famiglia: mio zio Paolo, mia zia Cristina, i miei cuginetti Aglaia e Achille e i miei nonni Luigi, Teresina e Luigia. Grazie per essermi sempre stati vicino e avermi insegnato tanto.

Ho voluto tenere per ultimi i miei genitori Angelo e Angela, sapete che per me siete la cosa più importante, siete un modello e una sicurezza. Senza di voi nulla di tutto questo sarebbe stato possibile, grazie di cuore.