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EXECUTIVE SUMMARY OF THE THESIS

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

LAUREA MAGISTRALE IN ENERGY ENGINEERING - INGEGNERIA ENERGETICA

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1. Introduction

Mobility sector is facing a dramatic change and its future is uncertain more than ever. The imperative need to reduce the environmental impact of transportation is pushing this transition and in this context Europe is willing to take a leading position. In order to substantially reduce CO_2 emissions from passenger cars different technologies are currently available. Automotive sector is particularly competitive and nowadays what appears to be the preferred short to mid term solution chosen by all the most important carmakers is represented by electric vehicles (EVs).

This study delves into the potential of a collective of EVs to offer ancillary services to the power grid. This is in light of the increasing share of EVs in the automobile market and the escalating demand for such services due to the expansion of variable renewable energy sources. In fact, a fleet of EVs, if properly aggregated, can act like a decentralised energy storage system, with the potential not only to reduce the detrimental impact of uncontrolled charging processes on the distribution grid, but also to actively contribute to grid stability control.

The methodology employed starts from mobility patterns registered in a vast geographical area and builds a bottom-up model to assess the behaviour of the overall fleet. The approach adopted is designed to be versatile and applicable to different areas, with a specific focus for this work on e-mobility in the Lombardy region. Similar studies like [1] and [2], adopt comparable bottom-up approaches to assess impact of charging processes, but limit their analysis to load shifting logics without proper integration with market products for grid stability. In research [1], authors have developed a spatial-temporal model (STM), integrating the transportation network into the electric grid. The study then focuses on the development of a peak shaving logics to limit harmful effects of unmanaged charging processes on distribution grids. In [2] instead, the optimal coupling between charging sessions scheduling and renewable energy production is investigated. The strong limitation of this work is that is based on data regarding trips of autonomous taxis that if on the one hand allow a detailed description of daily behaviour, on the other one represent an extremely small portion of the car fleet on the road.

The proposed methodology employs a traffic model that is able to dynamically account for traffic conditions on the transportation network while computing travel times. Thereafter an energy analysis allows to define time and space boundaries of charging processes. Then the model applies various control logics to assess the potential of the EVs' fleet in contributing to the products prescribed by the electric market for grid stability control. Finally the study provides a quantitative estimation of yearly revenues coming from the provision of modelled services.

2. Methodology

2.1. Traffic model

For the purpose of this research, data employed are from the *"Origin and Destination"* (OD) matrix created by *RegioneLombardia* [3], where a series of travels, representative of all travels taking place in a typical day, are collected. Each row of the matrix contains the province and the municipality of origin and of destination, the time frame (the hour of the day) in which the travel takes place and its reason (study, work, return home and leisure). The traffic model employed [4] combines information from the OD matrix with geospatial data relative to Lombardy's transportation grid. 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. Using travel time and not distance as the minimization goal, Dijkstra's shortest path algorithm selects the available route with the lowest overall travel time, providing consequently the arrival time.

2.2. Energy analysis

Among all travels it is firstly needed to select the ones performed by EVs and then determine which ones among them ask for a charging process. Given the current penetration assesses at a value lower than 1%, with the intention to model the near future it is chosen a penetration scenario for EVs at 2.5%. Then the process uses a Monte Carlo simulation to spread the travels performed by EVs among Lombardy's provinces, based on their current EV penetration.
The energy expenditure is then computed as the EV's last travel distance multiplied by a coefficient of 0.2 kW/km, representative of the current average energy consumption of EVs on the market. To distinguish between travels performed by EVs that require charging and those that do not, the study employs a probability-based method. To determine which travels are going to ask for charge it is assumed that the greater the energy consumed during a trip, the higher the likelihood the EV will need charging afterward. Consequently, EVs completing long trips with high energy consumption, are more likely to seek charging than those on shorter trips. However, there is still a chance that EVs with short trips might also require charging, presumably due to a low battery state. In these cases a progressive energy multiplier is applied to estimate the charging needs, reflecting this varied probability.
The study sets fundamental constraints for applying a modulation algorithm to EVs charging, focusing on defining the charging time boundaries. The lower limit is determined by the travel's arrival time at its destination while the upper limit is set by a parameter called *"stay time"*, representing the duration a vehicle is assumed to remain parked at the destination. This *"stay time"* varies based on the travel type and is modeled as a normal distribution around a typical number of hours.

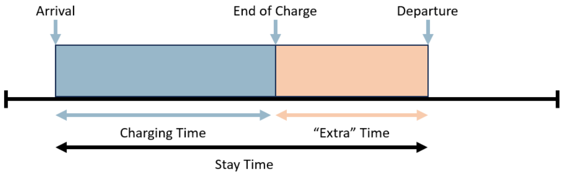

Figure 1: Stay times representation

The description provided in Figure 1 represents the basis of the proposed methodology. All developed algorithms deal with single charging processes in order to utilise the flexibility given by the *"Extra" time* to manipulate the charging power, while delivering the same amount of energy at the end of the *"stay time"*.
The model includes charging point availability to reflect infrastructure reality. In the envisioned scenario, the number of public charging points in Lombardy is projected at 15'000, approximately twice the current figure, following the increase of EVs diffusion. For domestic charging instead, it is assumed that *'return home'* travels requesting a charge can do so without any availability issues. Nominal power

output of each charging point is set to 6 kW for domestic chargers and split between 6 and 22 kW for public chargers, since for the objective of the research fast charging stations are not interesting since their main goal is to provide energy in the lowest possible time span. With a detailed understanding of the timing and power levels of the charging processes, it becomes possible to compute the additional load on the electrical grid by aggregating the contributions from all EV travels.

Among connected vehicles, the model considers an EV to be *"available"* for the provision of flexibility services, in a determined time window, if it can meet its charging needs while adjusting its power as required. This approach allows for assessing the number of connected EVs that can offer such services in any given time window and consequently the contribution that each vehicle can provide.

2.3. Primary frequency regulation

To contribute to primary frequency regulation provision, a group of EVs using smart charging (V1G) acts as a variable load. When the grid frequency deviates from the nominal one, the enabled units have to adjust and reestablish the power balance in the grid. To assess the amount of power to be modulated it is firstly determined the available band for this kind of service offerable by the aggregate. Its value is then used as ΔP_e in Equation (1), that allows to correlate a frequency variation to a power modulation.

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

To assess the available band it is considered that EVs' charging rate can be reduced simply by lowering the power output of the charging point performing the charging session, while for increasing the charge, charging stations must operate preventively below their nominal power to create a reserve capacity. The study caps the adjustment in charging power at 10% to have a slight impact on charging times and avoid stressing the power electronics and EV batteries. To minimise the impact on each single charging process the model distributes the requested power modulation among all *"available"* vehicles in the time frame when the service is requested. So the higher the number of *"available"* vehicles, the lower will be the required power deviation to each vehicle at equal request from the TSO.

2.4. Bands enhancement

To improve the contribution of the aggregate to primary regulation service provision it is developed a strategy that aims to enhance the band that can be guaranteed at any time of the day. The tactic is to delay charging sessions that begin during high-load periods, aiming to flatten the overall load profile by filling in the less busy periods. This approach varies depending on the travel type and "extra time" available (see Figure 1). *"Return home"* travels can be adjusted accounting only for the constraint on energy request, as they have no charging spot availability issues. For other travel types, it is necessary to consider also charging points' reservations immediately following the charging process in object when altering start times. This strategy allows to generate a more uniform daily availability for grid support services and consequently a more consistent participation in the offer of flexibility products in the market.

2.5. Tertiary reserve

In the description of tertiary reserve provision it is needed to include an evaluation about acceptance for the provision of the service by the TSO. Analysis of historical data from the Italian TSO (Terna), shows that the average acceptance rate for offers in the balancing market is about 5.5%. This particularly low value is coherent with current low competitiveness of renewable and distributed energy sources highlighted in [5] and [6]. This acceptance probability is influenced by two additional key factors: the price of the energy offered and the power capacity available from the provider. An acceptance model is used to assess whenever the aggregate is called to provide the service in exam. If selected, the EVs' pool adjusts its energy uptake either upwards or downwards for a whole hour to provide tertiary reserve. The bands assessment process is similar to the one described for primary frequency regulation but due to the longer duration and the need to ensure individual EVs are fully charged the availability of vehicles is lower with respect to the primary regulation case. Following the approach adopted for primary frequency regulation, the power deviation burden is split among all connected vehicles marked as *"available"* during time windows when the aggregate is called to provide tertiary reserve.

2.6. Unbalances

In the electricity market, participants must submit day-ahead production/consumption plans. With tertiary reserve provision combined to the constraint of fulfilling each vehicle energy request, unbalances in the opposite direction of the latest request are generated immediately after the provision of the service. A single unit's unbalance is assessed in context of the *zonal unbalance*, which aggregates all unbalances in a specific zone. A unit's unbalance exacerbates the situation if it aligns with the zonal unbalance, or mitigates it if opposite. The TSO handles these unbalances by imposing penalties based on the individual unbalance in the context of the zonal conditions. To deal with this effect two different approaches are adopted:

1. Compute unbalances generated and the relative penalty applied;
2. Accept a certain deviation from energy request for each single trip to avoid unbalances generation.

Regarding the computation of penalties two different possible algorithms are considered: *"dual pricing"* and *"single pricing"*, with the former more penalising for the unbalanced unit. Concerning the second approach, limits on the acceptable deviations from energy request are modelled and consequently all the previously presented processes are adapted and replicated. In Figure 2 it is reported a flowchart that summarises the presented methodology.

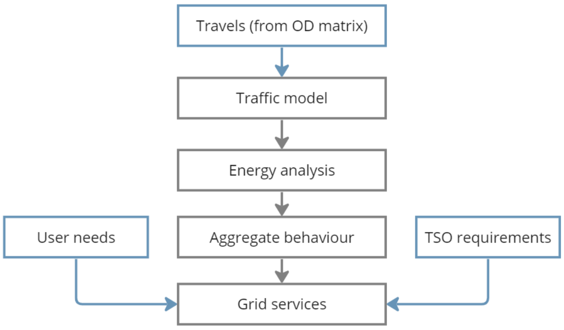

Figure 2: Methodology flowchart

3. Results

Simulations performed process the almost eight million travels taking place during a typical day in Lombardy, extract the 2.5% assumed to be performed by EVs and apply the logic described in Subsection 2.2 to determine which travels are going to ask for charge. At first a preliminary analysis on the occurrence of charging processes is performed. As shown in Figure 3 it is clear how two peak times can be identified for charge request: the first, mostly due to trips for work reason around 9 a.m., the other, related to *"return home"* trips around 18 p.m..

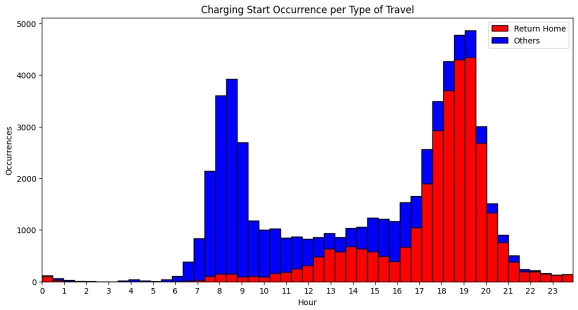

Figure 3: Occurrences of charging processes start

The proposed methodology allows to keep track of locations where charging processes take place, being able to identify the most stressed substations, typically located in urban areas, as depicted in Figure 4

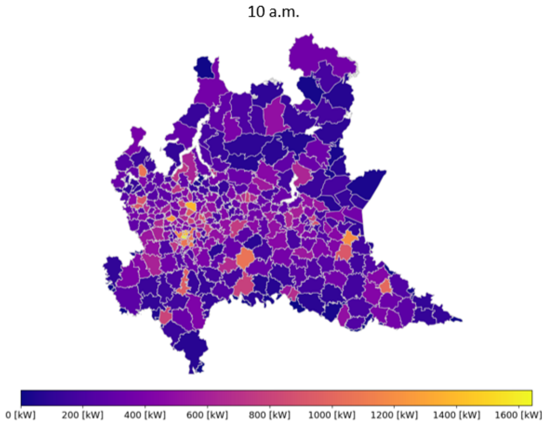

Figure 4: Added load spatial representation

After having determined the number of travels asking for charge and the number of charging points, the presented model allows to assess the embedded potential of the aggregate when providing different services. Firstly it is possible to distinguish the logics applied to the constraint

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 1: Presented simulations overview

relative to the energy request: whether it is accepted a certain deviation or not. Cases when flexibility is offered in both directions or not and whether the *"primary bands enhancement"* algorithm is applied are then identified. These options result in eight possible different simulations as reported in Table 1.

The output of the energy analysis presented in Subsection 2.2 is reported in Figure 5, where it is displayed the added load profile related to EVs' charging processes, with the contributions from charging sessions taking place at private and public locations highlighted in different colors. In Figure 6 it is instead shown the added load profile after the application of the strategy described in Subsection 2.4.

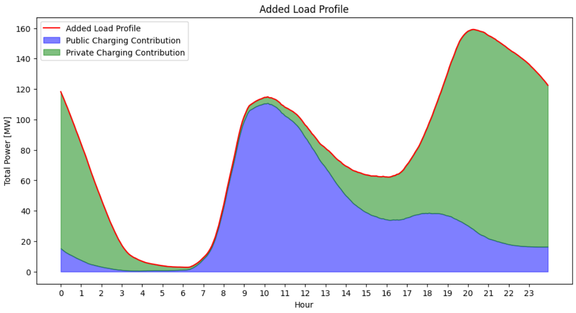

Figure 5: Added load profile

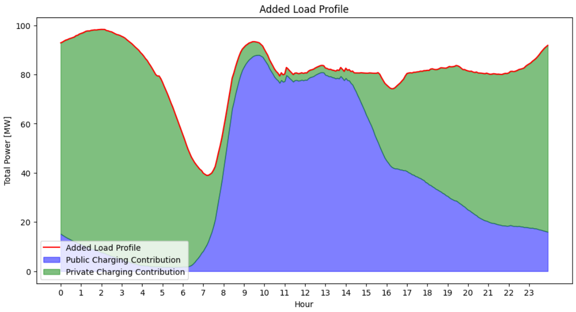

Figure 6: Added load profile after "primary bands enhancement" algorithm application

The bands for primary frequency regulation contribution are reported in Figure 5: with solid lines are indicated the bands after the application of the *"primary bands enhancement"* algorithm while with dashed lines the bands relative to the original load.

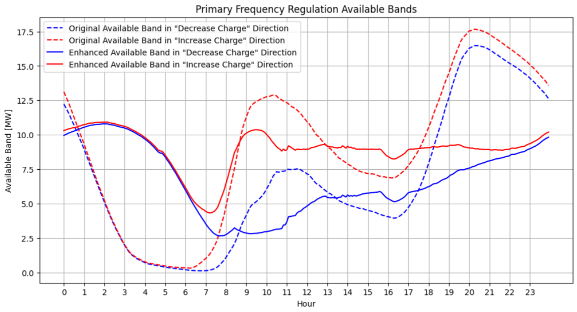

Figure 7: Available bands for primary frequency regulation

Regarding tertiary reserve provision in Table 2 are reported the probabilities of the pool to be accepted for the supply of the service in *"decrease charge"* direction resulting from the procedure presented in Subsection 2.5.

Probability of being accepted				
Hour of the year	1	2	3	...
Probability [%]	2.70	2.46	2.46	...

Table 2: Example of acceptance probabilities in "decrease charge" direction

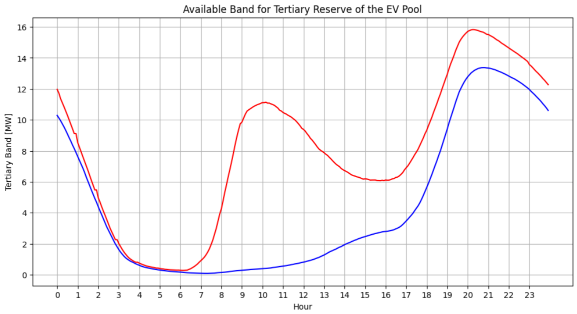

Figure 8: Available bands for tertiary reserve

From Figure 8 it is evident how the constraint regarding the energy request satisfaction limits consistently the available band in *"decrease charge"* direction, especially during daytime when charging stations availability is limited. In Figure 9 it is displayed the comparison of the load profile before and after the provision of tertiary reserve. It can be observed that from 9 to

10 a.m. the pool is called to increase the charging power and during the next hours it is evident the unbalance generated to satisfy vehicles' energy requests.

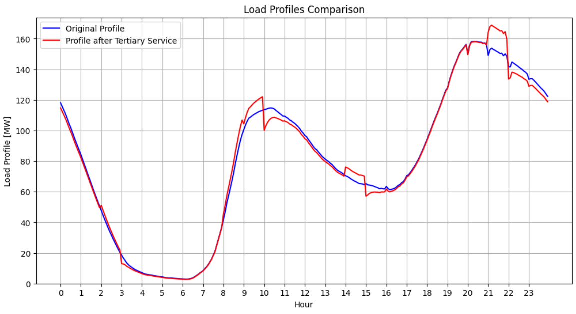

Figure 9: Impact of tertiary reserve on load profile

Running the model with the assumptions reported in Subsection 2.6 the availability for the provision of services raises thanks to the relaxation on the constraint about energy request fulfillment.

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 displayed in Figure 10 bands in increase and decrease direction are overlapped. The band coincides in both directions with the 10% of the load profile. This means the constraint on band values is dependent only on the limit in power modulation adopted by the methodology proposed and not anymore on energy request limitations.

In Figure 11 it is presented the impact on charging processes during the day with the highest number of calls for tertiary reserve.

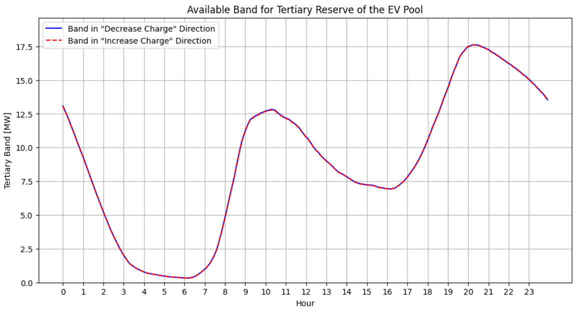

Figure 10: Available bands for tertiary reserve provision with impacted charge

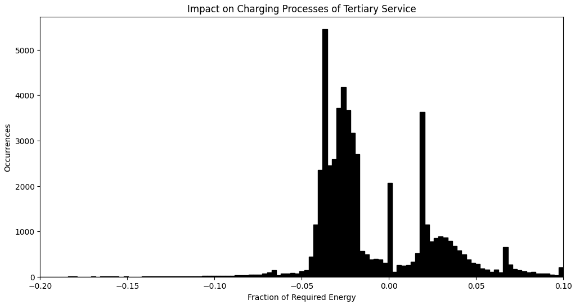

Figure 11: Deviation from required energy

3.1. Discussion

In Table 3 the minimum guaranteed values of primary frequency regulation bands are reported. The assessment of the minimum in both directions is essential due to the existing regulatory framework, which mandates that the primary frequency regulation band must be available in both directions. The minimum of the daily contribution is highlighted in Table 3. It is clear how the *"primary bands enhancement"* algorithm application is extremely impacting on this value. It allows the aggregate to offer a much more uniform availability, being able to contribute consistently throughout the day. After having assessed the quantitative potential participation in primary frequency regulation and tertiary reserve offered by the simulated fleet, the economic implications are analysed. Concerning primary frequency regulation, prices from central Europe market [7] are used. Band values are computed for each four hours window to fit price values available.

In addition, accordingly to current regulation, only simulations offering the service in both directions are considered to be accepted in the market. In Figure 12, an estimation of the yearly revenues coming from this service is reported.

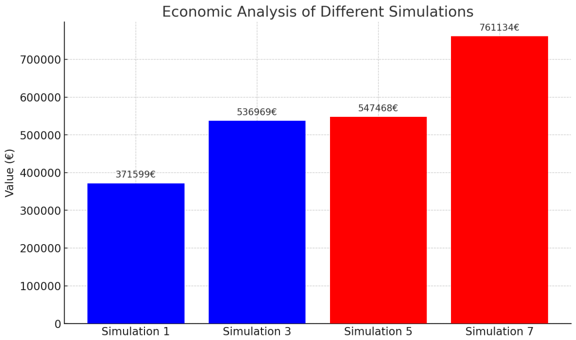

Figure 12: Yearly revenues from primary frequency regulation

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

Table 3: Summary of available band for different time slots across simulations

Bars in blue represent the two simulations performed with the *"full charge"* logic, while in red are shown the two adopting the *"impacted charge"* logic. Only simulations that offer flexibility in both directions are included. 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, highlighting the importance of proper load shifting logics application.

Regarding tertiary service provision instead, are considered offers by the aggregator that deviate of +/- 10% from the price on the Italian day ahead market. A moderate price deviation is chosen so as not to further reduce acceptance rates for tertiary reserve provision. In Figure 13 values of yearly revenues from tertiary reserve are reported for all the analysed simulations. The values are one order of magnitude lower than the ones associated to primary frequency regulation, mainly due to the low acceptance probabilities.

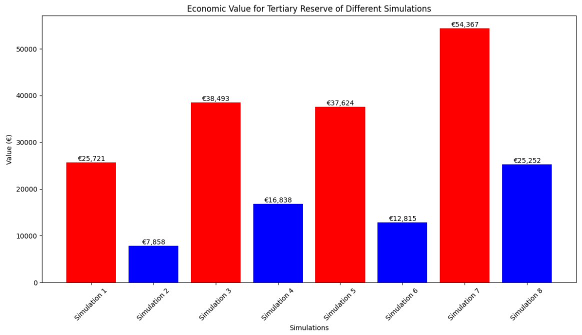

Figure 13: Yearly revenues from tertiary reserve provision

For the first four simulations, where constraint on full delivery of energy requested is imposed, penalties related to unbalances are evaluated both in case of *"double pricing"* or *"single pricing"* algorithm application. Values are computed running the simulation for all the 365 days of the year combining information on prices of day ahead marked and ancillary services market with accepted offers and zonal sign of northern Italy. From Figure 14, where yearly penalties associated with unbalances are reported, it is evident how the *"double pricing"* logic is far more penalising than the *"single pricing"* one.

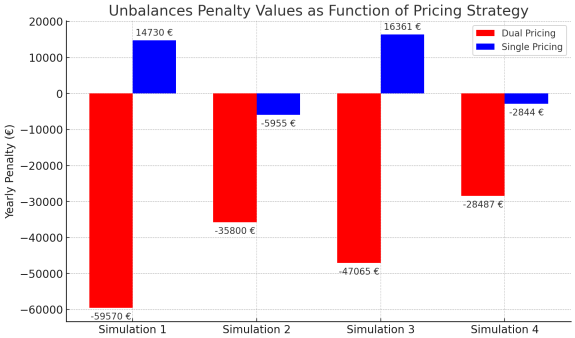

Figure 14: Yearly penalties for unbalances

The chart presented in Figure 15, confirms that primary frequency regulation represents 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. The mobility study in [3] indicates an average of 2.54 daily trips per vehicle. Using this value it is possible to estimate the number of EVs performing the modelled trips. The obtained number is around 75'000 so, dividing yearly revenues by this result the yearly earnings per vehicle are found, with a value slightly above €10 per vehicle. When evaluating this result it must be accounted that the impact of the proposed methodology on energy delivery is zero in case of *"full charge"* simulations or really slight in case of *"impacted charge"* scenarios as shown in Figure 11.

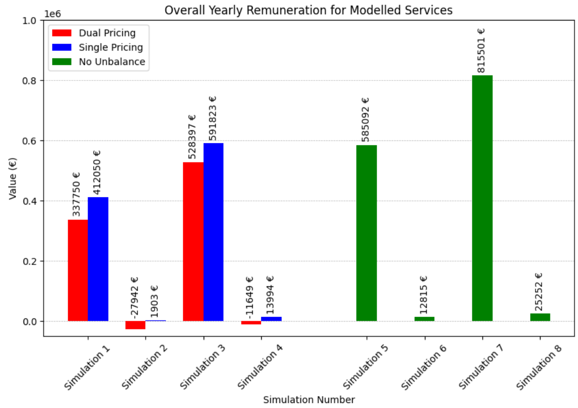

Figure 15: Overall yearly revenues

4. Conclusions

The work focuses on evaluating the potential of using a pool of EVs for the provision of ancillary services, starting from real data describing trips taking place in Lombardy region as a case study. The study highlights that with increased EV adoption, controlling charging processes becomes critical to avoid grid overloads and to leverage the decentralized energy storage potential of EVs for contributing to ancillary services. This is particularly relevant as the use of unpredictable renewable energy sources grows, increasing the demand for mentioned services. The study finds that the current selection process for tertiary reserve provision disadvantages resources with limited power, like the modeled EV aggregate. The recommendation for rulers is to relax the technical requirements and consider incorporating distributed storage solutions where possible, especially since they are economically viable due to their minimal service provision marginal costs. The thesis also suggests the adoption of a single pricing algorithm for evaluating unbalances caused by EV aggregates, which could economically benefit and encourage their participation in the ancillary services market. The remuneration for EV owners participating in such a scheme results to be modest, but the model is designed to have a minimal impact on charged energy. Therefore, a dedicated regulatory framework is recommended to facilitate EVs' participation in ancillary services. From the technical side, it is required an update in charging station infrastructure to enable real-time, secure communication with the overseeing entity that would control charging processes. The proposed methodology, faces challenges in accurately simulating the daily behaviors of individual vehicles, due to the lack of detailed data required for tracking each car's movements. This restricts a more detailed analysis of each vehicle's potential contribution to grid services and is the main suggested future improvement.

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