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E-Mobility Scheduling for the Provision of Ancillary Services to the Power System

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***Abstract*—In the present paper, the charging of an electric vehicles fleet is scheduled in order to provide power balance regulation to the electric grid. The starting of e-cars charging can be optimized according to predetermined limits set by users, in order to adjust the power exchange profile of the aggregated fleet. Ancillary services are sold on the Ancillary Services Market. Therefore, an analysis of the Italian Ancillary Services Market is provided to check the performance of the strategy proposed according to the actual market requirements. In this way, useful figures are provided to the reader in order to evaluate the technical and economic viability of the approach.**

***Index Terms*—Electric vehicles, ancillary services, scheduling, aggregation, power dispatch, optimization**

I. INTRODUCTION

Distributed Energy Resources (DERs), including non-programmable Renewable Energy Sources (RES), are historically excluded from electricity balancing in most of the liberalized electric markets so far in place. The participation in Ancillary Services Market (ASM), indeed, is limited by grid codes to programmable Production Units (PUs) of nominal power greater than a given threshold (e.g. in Italy this limit is set to 10 MVA [1]). However, with the increased spreading of energy harvesting from DERs, and the consequent reduction in the power production from conventional generators, the need to open the participation to the market to new flexibility resources is more and more arising [2]-[4]. In order to improve the power system's stability and reliability, recently the Italian regulatory authority opened the market, through pilot projects foreseen in Resolution 300/2017 [5], to dispersed and RES power plants, loads, energy storage systems and also e-mobility.

The largest pilot project currently ongoing is dedicated to virtual power plants gathering a mix of generation, load and storage units. It started in 2018 and allowed the participation to Italian ASM of more than 800 MW of DERs [6]. These pilot projects are foreseen to be a transient opportunity. The intentions of Italian regulatory authority are, anyway, to change markets' structure in the direction of steadily integrating DERs in balancing. This will be mainly done by the new electricity balancing regulation, under discussion in the second half of 2019 and in publication in 2020 [7].

In this framework, the present paper proposes the management of a fleet of Electric Vehicles (EVs) as a useful tool in the availability of an Aggregator to supply flexibility (e.g. ancillary services) to the power system. To this purpose, the charging of each EV included in the fleet is scheduled to match the power profile agreed on the market by the Aggregator, as result of Day-Ahead Market (DAM) commitments and the ancillary services sold on ASM. Therefore, the aggregator, gathering flexibility by this (partially) controllable load [8], can make offers on the market and profit from them.

With the just mentioned goal, a hybridization of the Artificial Bee Colony (h-ABC) [9] algorithm is used to schedule the charging processes, which operates by miming the behavior of a colony of bees in food foraging. In recent years, in the literature, it can be noticed an increasing interest in the exploitation of the storage capacity of EVs to perform services in support of the power grid [10]-[12]. Most of papers consider a bidirectional power exchange between EVs and the grid. The bidirectional "vehicle to grid" technology (V2G) has higher performances with respect to the unidirectional one (V1G) [13], but on the other hand, the regulation required, and the charging station infrastructures, are up to now critical problems in the V2G implementation [14]. In this regard, with a precautionary approach, in the present work, only the initial starting time of the EVs charging is managed by the control architecture, while no preemption nor V2G are considered.

Moreover, the meta-heuristic optimization procedure used in the paper (ABC algorithm) has been highly used in the literature to solve scheduling problems [15], also related to the EVs' charging [16], [17]. Furthermore, it is a common practice to overcome the disadvantages of the standard ABC by hybridization techniques [18], as done in this work. However, in the authors' knowledge, this is the first work that shows how an EVs fleet could participate to the ASM through an Aggregator. The merit of the presented research consists also in having simulated the behavior of each vehicle of the fleet by a realistic approach and using real data collected on the Italian ASM.

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In the following of the paper, in Section II, the methodology developed for the EVs scheduling is presented. In Section III the results obtained in the analysis of the Italian ASM are provided and commented. Then, in Section IV the model is tested, assuming as reference the Italian scenario, in order to prove its viability. Finally, some conclusions about the model's effectiveness are drawn.

II. METHODOLOGY PROPOSED

In the present paper, the supply of ancillary services to the power system is performed by scheduling the charging requests of e-mobility. The envisaged procedure operates as follows:

- At day D-1 the aggregator (or the balance responsible party having signed an agreement for the energy supply with the e-mobility customers) submits requests on the DAM to buy the amount of energy needed, on a predictive basis, to charge the vehicles. As a result, a binding day-ahead schedule of supply is defined, specifying the amount of energy that the EV fleet should absorb from the network at every hour of the next day.
- During the relevant ASM sessions (e.g. 4 h before the real-time), the aggregator submits bids for up/downward reserve, that are then selected by the TSO according to a pay-as-bid approach. The combination of DAM and ASM schedules represents a commitment toward the market that the Aggregator must respect; otherwise, it is subject to imbalance fees.
- During the day, up/downward regulations (up to the maximum value established in the market offers) can be requested to the Aggregator. Cars are used by customers and, when connected to a charging station, they are scheduled to meet the market commitments.

With the purpose of achieving a suitable trade-off between performance of the optimization procedure and computational effort required to solve the mathematical problem, a hybridization of the Artificial Bee Colony (ABC) algorithm is adopted for the EVs scheduling. The ABC is a swarm based meta-heuristic algorithm that was introduced by Karaboga in 2005 [9], modeling all the main factors affecting the behavior of a bee colony during the food foraging. The approach is based on three procedures computed iteratively to get closer to the solution of the problem: employed bee, onlooker bee and scout bee.

The most important phase of the research for new food sources (i.e. solutions of the problem) is the information exchange between the employed and onlooker bees. All information relevant to the food source associated with each employed bee is shared with other bees, and each onlooker bee has a higher probability to exploit the most profitable one. Hence, the number of onlooker bees assigned to a food source is proportional to its profitability [19].

To drive the scheduling process, a proper objective function needed to be adopted. In this regard, the main objective of the algorithm should be to guarantee satisfying performances in the provision of the ancillary services, at the same time preventing a reduction in the quality of the e-mobility service experienced by users. Therefore, the objective function should model these two aspects:

$$F_{\text{obj}} = \sum_{t=t_{\text{actual}}}^{t_{\text{actual}}+1h} a \left\| P_{\text{abs}}(t) - P_{\text{req}}(t) \right\| + \sum_{v=1}^{Tot_{cars}} b \cdot \text{Err}_{d,v} \tag{1}$$

where $P_{\text{abs}}(t)$ is the power actually absorbed at time t by all the charging cars; $P_{\text{req}}(t)$ is the power exchange requested according to the market schedule at time t; Err_d is the error committed in the case the scheduling causes the charging of the vehicle v not to be accomplished in the due time defined by the user, and a and b are the weighing parameters.

As one can observe, the optimization of the initial charging time of each vehicle is defined, according to (1), with respect to the following two objectives:

- In order to avoid economic penalties, it is necessary for the Aggregator to follow as much as possible the power schedule agreed on the market, resulting from the purchase on the Day-Ahead Market and the ancillary services sold on the ASM. If a gap is registered between the scheduled power and the absorbed one, it is considered a power imbalance and the Aggregator is subject to an economic fee proportional to the error.
- On the other hand, with the purpose of ensuring an optimal service to users, it is also necessary to fully recharge the EV battery before the planned departures. Therefore, the probability that a vehicle is picked up before the charge accomplishment should be limited. In this direction, an EV should be charged as soon as possible when connected to the charging station.

In (1), the first term is conceived to minimize the imbalance error with respect to the market schedule, while the second one contemplates the necessity to fully charge an EV before its departure. To simplify the optimization problem and reduce the computational effort, a linear combination of two parameters modeling the just mentioned aspects has been used. Moreover, given the different measurement units of the two parameters and their different weights in the selection of the best solution, two corrective parameters a and b have been introduced.

To set the final values of a and b, a backward method was implemented. A population of vehicles with fixed specifications (state of charge, time of arrival/departure) is created and then, for each car, it is defined the initial charging time, such that all the EVs reach a fully charged battery before their departure. Given the characteristics of each vehicle and selected the initial charging time, it is possible to compute the power absorbed by this population generated a priori. Then, several scheduling times are obtained with various optimizations conducted using different values of a and b, but using the same EV fleet and same power request. Hence, it is possible to choose the parameters generating the set of scheduling times closest to the ideal one.

The procedure optimizing the initial charging time is repeated each time a new EV is connected to a charging station and, to improve the performance of the scheduler, a prediction of future arrivals based on historical data is implemented.

A. Employed Bee Phase

In the standard ABC algorithm, the goal of the employed bee is to randomly search around the current food source hoping to find a better solution. In h-ABC, the employed bee phase is replaced with a deterministic heuristic that directs the research toward the optimal point achieving faster a solution. The heuristic designed in this work modifies the charging starting time of a single vehicle for each iteration, choosing the most appropriate one by considering both the necessity of filling the gap between the requested and absorbed power and simultaneously maintain a high quality of the e-mobility service. The employed bee is applied to different randomly generated initial populations of EVs. Through this approach, a different solution is obtained at each run. Reiterating the heuristic procedure several times, it is possible to improve the objective function. However, despite the random generation of the initial population, because of the deterministic behavior of the employed bee, the reiteration could produce a higher standardization of the food sources in output to the process. Therefore, it is crucial to find a number of consecutive heuristic iterations providing a good compromise between maintaining high diversity among populations and improvement of the objective function.

B. Onlooker Bee Phase

The onlooker bee phase is executed at the end of the iterations of the heuristic searcher and its purpose is to focus the research near promising populations. Indeed, the onlooker bees are more likely to search around food sources with low value objective function.

In this work, a general structure of the onlooker bee phase similar to the one commonly proposed in [20] is adopted, with some adjustments to avoid neglecting apparently less promising food sources. Indeed, the distributed probability function used by the onlooker bee is changed according to:

$$P_e = F_e \big/ \sum F_e \tag{2}$$

where:

$$F_e = \exp\left(\frac{-F_{\mathrm{obj},e}}{\mathrm{mean}(F_{\mathrm{obj},e})}\right) \tag{3}$$

In (3), $F_{\mathrm{obj},e}$ are the values of the objective function assumed at the end of each iteration of the employed bee phase.

C. Scout Bee Phase

The scout bee is the last phase of the h-ABC. Its purpose is to avoid the unjustified exploration of regions around a current food source that has been already exploited. In particular, the algorithm considers that a region around a solution has been completely explored when the number of researches around it is higher than a given threshold.

A food source that has been completely explored it is abandoned and the corresponding employed bee is reassigned to a new food source. This phase is very important in order to avoid the solution to be stacked in a local minimum and permits to evaluate other possible food sources located in other parts of the domain [21].

III. ANALYSIS OF THE ITALIAN MARKET SCENARIO

In the following of the present paper, the effectiveness of the ABC model proposed is assessed by using the real data collected on the Italian ASM. To feed the model with realistic dispatching orders for up/downward regulation, a statistical analysis of the Italian balancing market has been carried out.

ASM in Italy presents multiple sessions per day: ex-ante sessions for clearing congestions and building reserves (ex-ante ASM) and, in the Balancing Market (BM), real-time sessions for delivering flexibility services. Two main products are traded in both markets: Secondary Regulation, corresponding to automatic Frequency Restoration Reserve (aFRR); “Other Services”, including manual Frequency Restoration Reserve (mFRR), Replacement Reserve (RR) and congestion management.

Each dispatching order can be modeled as follows. The order duration is a multiple of a quarter hour, while its direction is a power injection into the grid (i.e. less withdrawal from the grid with respect to the baseline) in case of upward regulation, vice versa (i.e. more withdrawal with respect to baseline) in the case of downward. The magnitude of the dispatching order is constant within the quarter hour, with awarded quantity (Q_{awd}) with respect to pre-selected quantity (Q_{adj}) limited within the following interval:

$$0 < \frac{Q_{\mathrm{awd}}}{Q_{\mathrm{adj}}} \leq 1 \tag{4}$$

where Q_{adj} is the available quantity, offered by the ancillary service provider and pre-selected by the TSO. If an offer is accepted, then, in the real-time, the provider can be asked to supply an up/downward regulation up to Q_{adj}. Therefore, the analysis aims to return the statistical distribution for the duration and magnitude of the ratio $Q_{\mathrm{awd}}/Q_{\mathrm{adj}}$. The output of this study will be then given in input to the e-mobility scheduling algorithm. This scheme, consisting of a quarter hour reference period, is shared by other ancillary services schemes [22], [23], so that results obtained in the study hold an acceptable degree of replicability also for other EU’s countries.

The data relevant to “Other services” traded in the Italian ASM during 2018 (including congestion management, mFRR and RR) have been extracted to this purpose by Italian market operator (GME) online database [24]. According to the rules in place in Italy, market players can bid with a cost curve up to 4 steps. Considering that DERs are beginners in the market and assuming a simplified offer strategy by them, only the first step has been selected (around 65% of total offers).

Furthermore, only awarded offers have been selected (i.e. rejected offers are not considered), since the aim is characterizing a likely dispatching order, despite the probability of acceptance. The query returned around 390k quarter hourly offers for upward and 190k offers for downward regulation from PUs. Each offer is characterized by the PU name, the date, the hour, the quarter hour (i.e. 1 to 4), the offered quantity (Q_{off}) and price (P_{off}), the adjusted quantity (Q_{adj}), the awarded quantity (Q_{awd}) and price (P_{awd}).

Q_{off}, Q_{adj} and Q_{awd} represent the three consequential steps of a bid in Italian BM [1].

Before the market gate closure, the PU managers offer Q_{off} on the market to declare the willingness to provide that regulation, requesting P_{off} as remuneration (in €/MWh).

After gate closure but before real time, the Italian TSO adjusts Q_{off}, which becomes Q_{adj} as available quantity by the PU (considering the outcomes of DAM and Intraday Market, hence possible errors in bidding by PU's manager, etc.).

Then, in real-time, Q_{awd} is asked for regulation by TSO's dispatching orders and is provided by the PU. It is remunerated at P_{awd}. P_{awd} is always equal to P_{off}, except for the cases in which there is an incompatibility of P_{off} with respect to prescriptions in grid code (e.g. negative prices): these exceptional cases are neglected in this study.

The results of the statistical study are presented in Fig. 1. The duration of each order can be approximated with a lognormal distribution, for both upward and downward requests, featuring the mean values and variances presented in Table I.

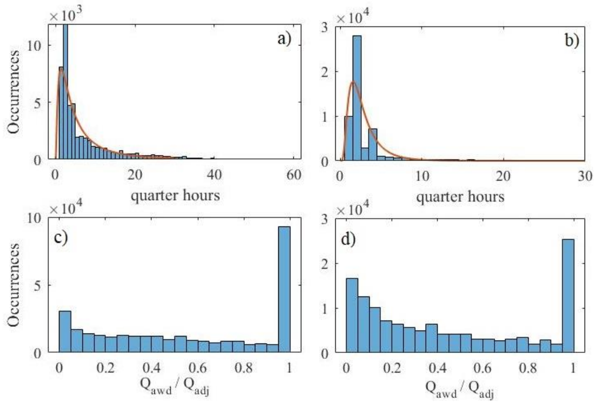

Fig. 1. Probability distribution for a) upward and b) downward dispatching order duration, and probability distribution for c) upward and d) downward order awarded ratio.

TABLE I: MEAN AND VARIANCE OF LOGNORMAL DISTRIBUTION APPROXIMATING DISPATCHING DURATION

Parameter	Upward	Downward
Mean value	1.427	0.844
Variance	1.039	0.638

IV. NUMERICAL RESULTS ON ASM PARTICIPATION

The performances of the proposed h-ABC algorithm in the supply of ASM regulations are evaluated, also comparing how the quality of the e-mobility services and the amount of the imbalance fees change with respect to two reference scenarios. In the first one, denominated "No Sch" scenario, the scheduler is not used, so each vehicle starts charging when connected to a station. This scenario represents the current practice in place for the e-mobility: each EV is charged as soon as possible, without any optimization, and without the provision of ancillary services to the power grid. Furthermore, to be able to analyze the impact of the ancillary services on the vehicle fleet, also the case in which the scheduling is performed without regulation requests by TSO is examined ("No ASM" scenario). These reference scenarios are compared with 12 simulations in which the software optimizes the charging process to participate to the ASM. A magnitude for up/downward regulations of 105 kW is supposed, equal to about the 43% of the mean power absorbed by the EVs aggregate during the day. To perform upward services (Up_i), a reduction of the power absorbed from the grid will be requested to the EVs fleet; vice versa, a downward regulation (Down_i) implies an increase in its power consumption. The time duration of the simulated ancillary services has been chosen consistently with the statistical data reported in previous Section II. Indeed, the durations of dispatching orders reported in the table represent those that, according to the market analyses, have shown the higher occurrence: 81.88% of upward regulations have a duration equal to or shorter than 3 h, while for downward requests the percentage rises to 95.80%.

TABLE II: MAIN CHARACTERISTICS OF THE SIMULATED ANCILLARY SERVICE REQUEST

Scenario	Duration [h]	Absorbed Power [kW]	Energy Variation [%]
Up_1	0.5	-105	-0.898
Up_2	1	-105	-1.796
Up_3	1.5	-105	-2.694
Up_4	2	-105	-3.592
Up_5	2.5	-105	-4.490
Up_6	3	-105	-5.388
Down_1	0.5	+105	+0.898
Down_2	1	+105	+1.796
Down_3	1.5	+105	+2.694
Down_4	2	+105	+3.592
Down_5	2.5	+105	+4.490
Down_6	3	+105	+5.388

In Table II, the main characteristics of the simulated ancillary services are presented. The first column reports the simulated scenario, the second and the third ones show respectively the duration of the upward/downward request and its power amplitude (variation compared to the baseline). The last row considers the percentage of energy variation due to the ASM regulation with respect to the daily energy absorbed by the charging stations. In all cases, the simulated vehicle fleet is composed of 1500 EVs and the behavior of each vehicle is modeled by using a stochastic approach based on real statistical data [25]. Furthermore, a simulated time interval of 3 days has been considered, and the regulation service has been performed in the central day (2nd day), to eliminate all edge-effects. To evaluate the performances, two KPIs have been defined. The first one ($|E_{rr}|$) is the ratio between the sum of the absolute value of the imbalance divided by the total energy absorbed by the aggregate in the "No Sch" scenario. The second one, $P(\text{SoC}<p)$ represents the percentage of the vehicles that leaves the charging station with a state of charge (SoC) lower than p.

First of all, the proposed model allows buying the amount of energy required on the DAM on the basis of a forecast of EV charging requests for the next day. Fig. 2 shows the comparison between the hourly energy purchase on the DAM (Pow DAM) and the power that would be absorbed without e-mobility scheduling (Pow No Sch). Since it is difficult to predict accurately the behavior of private cars, the DAM curve could be considerably different with respect to the actual absorbed power. Hence, in absence of scheduling, a high economic penalty could be applied to the Aggregator. Furthermore, the absence of scheduling will exclude profits from the ASM regulation.

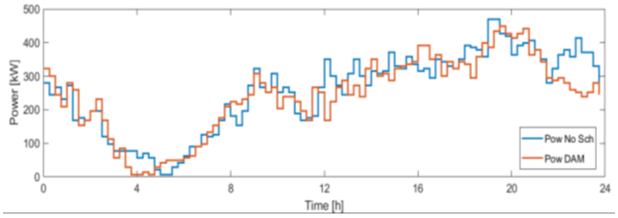

Fig. 2. Comparison between DAM curve and the power absorbed without smart scheduling (*N_o* Sch scenario).

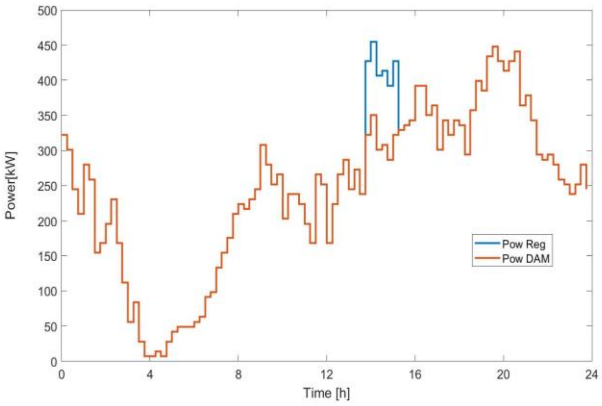

Fig. 3. Comparison between the power bought in the DAM and the curve after the Down_3 regulation request.

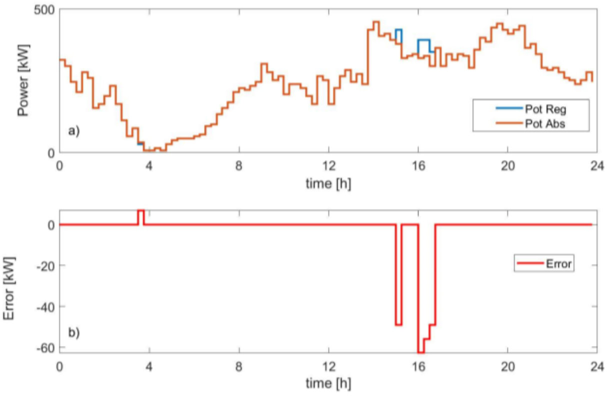

Fig. 4. Comparison between the power absorbed and the power requested in Down_3 regulation (a), and the corresponding imbalance errors (b).

TABLE III: RESULTS OF THE SIMULATED AND REFERENCE CASES

Scenario	E_{abs} [MWh]	$\lvert E_{rr}\rvert$ [%]	P(SoC =1) [%]	P(SoC<0.95) [%]
No Sch	6.111	16.013	92.500	5.300
No ASM	5.919	0.030	90.486	5.502
Up_1	5.866	0.029	90.420	5.566
Up_2	5.814	0.029	90.485	5.502
Up_3	5.761	0.029	90.356	5.502
Up_4	5.709	0.029	90.421	5.502
Up_5	5.656	0.029	90.421	5.502
Up_6	5.604	0.029	90.356	5.502
Down_1	5.971	0.029	90.485	5.502
Down_2	6.024	0.229	90.485	5.502
Down_3	6.076	0.916	90.485	5.502
Down_4	6.129	1.690	90.485	5.502
Down_5	6.181	2.549	90.485	5.502
Down_6	6.234	3.408	90.485	5.502

Fig. 3 reports the comparison between the hourly power purchase on the DAM and the change in the power absorption due to the real-time regulation requests (Down_3). As it is possible to observe from Fig. 4. (a), the scheduling allows following almost perfectly the DAM power curve and the regulation signal, strongly limiting the imbalance error (see Fig. 4. (b)).

In Table III, a comparison between the main outputs of the 12 simulated scenarios and the results of the corresponding reference scenarios is reported. The proposed algorithm permits not only to reduce the prediction error with respect to the DAM commitments of Fig. 1, but also to perform a high-quality regulation service, maintaining the mean SoC near the unitary value (full charge) of the vehicle fleet by exploiting its flexibility.

Indeed, the results in terms of relative imbalance error obtained with the algorithm ($|E_{rr}|$) and distribution of the SoC of the simulated vehicles (P(SoC)) highlight the high performances of the scheduling process. As general trend, it is possible to observe that the algorithm is very effective in following the required power curve (Pow Reg) especially during upward regulations, in which a reduction of the power absorbed is required (and therefore charging processes are delayed). On the contrary, during downward regulations (increase of power absorbed from the network), it could happen that the scheduling is not able to follow the requested power curve due to a lack of vehicles connected to charging stations.

Analyzing the SoC distribution of the EV fleet, it can be noticed that it is negligibly affected by regulation requests. Indeed, both in the "No Sch" and "No ASM" scenarios, the percentage of EVs with a SoC lower than 0.95 is almost constant. This could be explained by the fact that the proposed algorithm postpones the charging process of vehicles with high possibility to be completely charged in the future. The presence of EVs not fully charged also without scheduling (No Sch) is a consequence of users behavior, which stop to a charging station for a time that is not enough for achieving the complete charging (this occurs in 5.3% of the total stops). On the other hand, Table III shows that the h-ABC scheduling reduces the imbalance errors of almost three order of magnitude (16.013% in the "No Sch" scenario vs 0.030% in the "No ASM" scenario).

V. CONCLUSION

In the present paper, an h-ABC algorithm for the scheduling of charging requests of an EV fleet has been presented. The main objective is to extend the participation to the Ancillary Service Market to new entities, allowing for the harvesting of flexibility also from the e-mobility as support to the power system. The approach proposed is compliant with the recent evolutions in the Italian regulatory framework, and it can be considered a key to meet the decarbonization targets set in perspective by EU.

The analysis of the Italian ASM allowed for the evaluation of the model's performance according to the characteristics of the dispatching requests actually delivered on the ASM to ancillary service providers. In this way, the figures provided in the paper can be considered a valuable reference to evaluate the technical and economic viability of the approach. As a matter of fact, it proved to be very effective in limiting the forecasting error affecting the commitments on the DAM and the imbalance error in the ancillary services provision. Finally, another important fact highlighted by the results is the effectiveness of the optimization method in preserving the quality of the e-mobility service, preventing an unwanted and excessive reduction in the vehicles' SoC.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

F. Gulotta and D. Falabretti conceived the presented idea based on previous works done by the research group (D. Falabretti, M. Merlo, M. Moncecchi). The code for the electric vehicles scheduling was developed by F. Gulotta and D. Falabretti. The market analysis presented in Section III was carried out by A. Blaco, F. Bovera and G. Rancilio. All authors discussed the approach and results, contributed to the final manuscript and had approved it.

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