Electric Vehicles as Frequency Containment Reserve Providers

Ivan Pavić
University of Zagreb Faculty of Electrical Engineering and Computing
Zagreb, Croatia
ivan.pavic@fer.hr

Hrvoje Pandžić
University of Zagreb Faculty of Electrical Engineering and Computing
Zagreb, Croatia
hrvoje.pandzic@fer.hr

Tomislav Capuder
University of Zagreb Faculty of Electrical Engineering and Computing
Zagreb, Croatia
tomislav.capuder@fer.hr

***Abstract*—Integration of renewable energy sources accompanied with decommission of fossil fueled power plants inherently results in lack of power system flexibility. In turn, this reduced flexibility calls for additional balancing services. In parallel to this, the process of transport sector electrification is in place and the large fleets of electric vehicles (EVs) could prove to be one of the solutions for increased power system flexibility needs. If managed adequately, EVs could be able to provide the missing balancing services. In this paper, a model of EV day-ahead market and frequency containment reserve bidding is defined in order to asses the potential challenges that could arise during such service provision. Special attention is given to the EV battery state of energy, since the batteries are energy-limited resources and specific issues may arise both at individual EV and fleet level.**

***Index Terms*—Electric Vehicles, Electric Vehicle Fleet, Electric Vehicle Aggregator, Frequency Containment Reserve, Primary Reserve**

I. Introduction

Electrification of the transport sector is in the progress and electric vehicles (EVs) are rapidly increasing their market share. According to [1], EVs' share in total vehicles sales in China in 2018 is more then 4%, while in Europe and USA these numbers are around 2.5%. Document [1] also states that such trend will intensify in the future and a significant effect on power system operation will be obvious since the forecast electricity consumption increase from 2018 to 2030 is 10 to 20 times. Similar conclusions can be found in [2] and [3], where the authors argue that EVs' energy consumption can be supplied with the current infrastructure. However, the problem lies in the high increase in power demand, which could increase the network congestion and create the need for additional peak generation. In order to overcame those issues, the EVs smart charging principle is highly supported. The term smart charging refers to controllable charging (and possible discharging) according to the power system needs. Apart from the issues of simultaneous charging and therefore local and/or global peak demand increase, smart charging is also seen as a flexibility enhancement tool where EVs are proposed to provide various ancillary services.

This paper is funded in part by the Croatian Science Foundation under the projects: Active NeIghborhoods energy Markets pArTicipatION – ANIMATION, Innovative Modelling and Laboratory Tested Solutions for Next Generation of Distribution Networks - IMAGINE, and Flexibility of Converter-based Microgrids - FLEXIBASE.

Power system flexibility requirements are on the rise due to the heavy decarbonisation measures in the form of Renewable Energy Sources (RES) increase [4], [5], and [6]. In general, wind and solar variability and uncertainty increase ramping and balancing needs. Parallel to the RES increase, decarbonisation also entails decommission of controllable fossil fueled power plants traditionally used for providing flexibility to the power system. Surely, a new flexibility providers must be procured to secure stable and non-disrupted power system operation. This paper discusses how an EV fleet can be used to provide balancing reserve to the transmission system operator through a new model of an aggregated EV fleet, but still respecting all the individual EV behavior and constraints.

Balancing reserves in Europe are divided into automatic and manual. The automatic reserves are Frequency Containment Reserve (FCR) and automatic Frequency Restoration Reserve (aFRR), while the manual reserves are manual Frequency Restoration Reserve (mFRR) and Replacement Reserves (RR). In this paper we focus on FCR, which in the European Union Internal Electricity Balancing Market denote operating reserves necessary for constant containment of frequency deviations (fluctuations) from the nominal value in order to constantly maintain power balance in the whole synchronously interconnected system [7]. The EV FCR provision can bear some additional costs such as investment in bidirectional charging equipment. Profitability of such investment highly depends on the FCR design type, FCR price range and the amount of such investment [8]. The EV aggregator bidding strategies in the day-ahead energy and FCR markets depend on the EV behavior stochasticity. Thus, integrating uncertainty in mathematical models yields higher revenues [9]. FCR is activated when frequency diverges form its nominal value and, from the technical viewpoint, EVs are perfectly able to provide FCR timely and accurately when needed [10]. Apart from the EV behavior uncertainty, the price uncertainty also plays a crucial role in profitability of an EV aggregator bidding strategy in both the day-ahead energy and FCR markets [11]. The high revenue streams from FCR provision can provide sufficient return to cover a significant part of the EV charging costs.

978-1-7281-2956-3/20/$31.00 ©2020 IEEE

The review shows that different aspects are considered when EVs are observed as energy and reserve market participants. While some of the papers tackle the issue of price or EV behaviour uncertainty none of the takes into account reserve activation uncertainty. The main contribution of this paper is to demonstrate how an EV fleet behaves when providing FCR in developed European markets and how the uncertain FCR activations affect EV and EV fleet SOE. Direct modeling of individual EV constraints and usage of real FCR activation data provides an insight how an EV aggregator should organise its bidding strategy in the DAM and FCR market. The focus of the paper is not to create stochastic bidding model but to check how such uncertainty affects the EV fleet and individual EVs in the real time.

II. Mathematical Formulation

A. Nomenclature

1) Sets and Indices:

$\mathcal{T}$ Set of time steps, indexed by t.
$\mathcal{V}$ Set of vehicles, indexed by v.
$\mathcal{CP}$ Set of charging points, indexed by cp.

2) Input parameters:

$A_{s,t}^{\text{UP\_FCR}}$ Up FCR activation vs reservation ratio for s at t,
$A_{s,t}^{\text{DN\_FCR}}$ Down FCR activation vs reservation ratio for s at t,
C_v^{BAT} Capital battery cost of vehicle v (€).
C_t^{FCH} Fast charging fee (€/kWh).
C_t^{DAM} Day-ahead market electricity price at t (€/kWh).
$CR_t^{\text{UP\_RES}}$ Reservation fee for either upward FCR or aFRR at t (€/kW),
$CR_t^{\text{DN\_RES}}$ Reservation fee for either downward FCR or aFRR at t (€/kW),
CAP_v^{BAT} Battery capacity of vehicle v (kWh).
$D_{1,2,3,4}^{\text{BAT}}$ Battery degradation coefficients.
$E_{v,t}^{\text{CP\_MAX}}$ Maximum energy limit for v at t due to charging point installed power limits (kWh).
$E_{v,t}^{\text{OBC\_MAX}}$ Maximum energy limit for v at t due to on-board-charger installed power limits (kWh).
$E^{\text{FCH\_MAX}}$ Maximum energy limit for fast charging point (kWh) at certain time-step.
$E_{v,t}^{\text{RUN}}$ Energy consumed for mobility purposes in vehicle v at t (kWh).
SOE_v^{MIN} Minimum allowed SOE of vehicle v (%).
SOE_v^{MAX} Maximum allowed SOE of vehicle v (%).
SOE_v^{0} Initial SOE of vehicle v (%).
SOE^{CV} Constant voltage charging phase knee point (%).
η^{DCH} EV V2G discharging efficiency.
η^{FCH} EV fast charging efficiency.
η^{RUN} EV mobility discharging efficiency.
η^{SCH} EV slow charging efficiency.

3) Variables:

$e_{v,t}^{\text{BUY\_DAM}}$ Energy bought for v at t on the day-ahead market (kWh).
$e_{v,t}^{\text{SELL\_DAM}}$ Energy sold from v at t on the day-ahead market (kWh).
$c_{v,t}^{\text{DEG}}$ Degradation cost of vehicle v at time t (€).
$e_{v,t}^{\text{DCH}}$ Energy discharged from vehicle v at t (kWh).
$e_{v,t}^{\text{FCH}}$ Energy fast charged to vehicle v at time t (kWh).
$e_{v,t}^{\text{SCH}}$ Energy slow charged to vehicle v at time t (kWh).
$soe_{v,t}^{\text{EV}}$ State-of-energy of vehicle v at time t (kWh).
$r_{v,t}^{\text{UP\_FCR}}$ Reserved capacity of v at t on either upward FCR or aFRR market.
$r_{v,t}^{\text{DN\_FCR}}$ Reserved capacity of v at t on either downward FCR or aFRR market.
$r_{v,t}^{\text{UP}}$ Maximum capacity of v at t in upward direction.
$r_{v,t}^{\text{DN}}$ Maximum capacity of v at t in downward direction.

B. Mathematical Model

The mathematical model is a minimization of the energy cost purchased in the DAM minus the sold FCR up and down capacities.

$$\min_{\Xi_{\text{OF}}} c^{\text{EVBA}} = \sum_{t=1}^{N_t}\sum_{v=1}^{N_v} e_{v,t}^{\text{BUY\_DAM}} \cdot C_t^{\text{DAM}} - e_{v,t}^{\text{SELL\_DAM}} \cdot C_t^{\text{DAM}} - r_{v,t}^{\text{UP\_FCR}} \cdot CR_t^{\text{UP\_FCR}} - r_{v,t}^{\text{DN\_FCR}} \cdot CR_t^{\text{DN\_FCR}} \; e_{v,t}^{\text{FCH}} \cdot C_t^{\text{FCH}} + c_{v,t}^{\text{DEG}} \tag{1}$$

Amount of capacities which could be traded is limited with charging/discharging power/energy constraints:

$$e_{v,t}^{\text{BUY\_DAM}}, e_{v,t}^{\text{SELL\_DAM}} \geq 0 \quad \forall v,t \in V,T; \tag{2}$$
$$r_{v,t}^{\text{UP\_FCR}}, r_{v,t}^{\text{DN\_FCR}} \geq 0 \quad \forall v,t \in V,T; \tag{3}$$
$$r_{v,t}^{\text{UP}}, r_{v,t}^{\text{DN}} \leq E_v^{\text{OBC\_MAX}} \quad \forall v,t \in V,T; \tag{4}$$
$$r_{v,t}^{\text{UP}}, r_{v,t}^{\text{DN}} \leq E_{v,t,cp}^{\text{CP\_MAX}} \quad \forall v,t,cp \in V,T,CP; \tag{5}$$
$$r_{v,t}^{\text{UP}} \leq soe_{s,v,t}^{\text{EV}} - SOE^{\text{MIN}} \cdot CAP_v^{\text{BAT}} \quad \forall s,v,t \in S,V,T; \tag{6}$$
$$r_{v,t}^{\text{DN}} \leq SOE^{\text{MAX}} \cdot CAP_v^{\text{BAT}} - soe_{s,v,t}^{\text{EV}} \quad \forall s,v,t \in S,V,T; \tag{7}$$
$$r_{v,t}^{\text{DN}} \leq E_v^{\text{OBC\_MAX}} \cdot \frac{1 - soe_{s,v,t}^{\text{EV}}}{1 - SOE^{\text{CV}} \cdot CAP_v^{\text{BAT}}} \quad \forall s,v,t \in S,V,T; \tag{8}$$

$$r_{v,t}^{\text{UP}} \geq e_{v,t}^{\text{SELL\_DAM}}/DT - e_{v,t}^{\text{BUY\_DAM}}/DT + r_{v,t}^{\text{UP\_FCR}} \quad \forall v,t \in V,T; \tag{9}$$
$$r_{v,t}^{\text{DN}} \geq e_{v,t}^{\text{BUY\_DAM}}/DT - e_{v,t}^{\text{SELL\_DAM}}/DT + r_{v,t}^{\text{DN\_FCR}} \quad \forall v,t \in V,T; \tag{10}$$

$$e_{s,v,t}^{\text{CH}} - e_{s,v,t}^{\text{DCH}} = e_{v,t}^{\text{BUY\_DAM}} - e_{v,t}^{\text{SELL\_DAM}} + r_{v,t}^{\text{DN\_FCR}} \cdot A_{s,t}^{\text{DN\_FCR}} \cdot DT - r_{v,t}^{\text{UP\_FCR}} \cdot A_{s,t}^{\text{UP\_FCR}} \cdot DT \quad \forall s,v,t \in S,V,T; \tag{11}$$
$$e_{v,t}^{\text{FCH}} \leq E_t^{\text{FCH\_MAX}} \quad \forall v,t \in V,T; \tag{12}$$

Eqs. (2) and (3) set the four bidding variables as positive. Eq. (4) constrains the charging/discharging power to the On-Board Charger (OBC) capacity, while eq. (5) constrains the charging/discharging power to the Charging Point (CP) capacity. Variables r^{DN} and r^{UP} refer to maximal power that an EV can charge (or go down) and discharge (or go up), respectively, while $r^{\text{DN\_FCR}}$ and $r^{\text{UP\_FCR}}$ refer to bids for FCR down and up provision, respectively. Eqs. (6) and (7) limit the maximum discharging and charging power considering minimum/maximum State-Of-Energy (SOE). Charging power is additionally constrained in eq. (8) for higher values of SOE due to reduced charging speed at the constant voltage phase of the li-ion battery charging process. Eqs. (9) and (10) allocate the maximum discharging/charging power between the DAM Sell/Buy ($e_{v,t}^{\text{SELL\_DAM}}$ and $e_{v,t}^{\text{BUY\_DAM}}$) energy and FCR DN/UP reserve activations ($r_{v,t}^{\text{DN\_FCR}} \cdot A_{s,t}^{\text{DN\_FCR}} \cdot DT$ and $r_{v,t}^{\text{UP\_FCR}} \cdot A_{s,t}^{\text{UP\_FCR}} \cdot DT$). Parameters $A_{s,t}^{\text{DN\_FCR}}$ and $A_{s,t}^{\text{UP\_FCR}}$ are calculated based on the ratio of total accepted FCR UP/DN reserve and actual activated reserves.

$$c_{s,v,t}^{\text{DEG}} >= C_v^{\text{BAT}} \cdot (D_1^{\text{BAT}} + D_2^{\text{BAT}} \cdot \frac{e_{s,v,t}^{\text{DCH}}}{CAP_v^{\text{BAT}}} \cdot 100$$
$$+D_3^{\text{BAT}} \cdot \frac{1 - soe_{s,v,t}^{\text{EV}}}{CAP_v^{\text{BAT}}} \cdot 100) \quad \forall s, v, t \in S, V, T; \qquad (13)$$

$$c_{s,v,t}^{\text{DEG}} >= C_v^{\text{BAT}} \cdot (D_4^{\text{BAT}} \cdot \frac{e_{s,v,t}^{\text{DCH}}}{CAP_v^{\text{BAT}}} \cdot 100)$$
$$\forall s, v, t \in S, V, T; \qquad (14)$$

Li-ion batteries are prone to degradation, especially when cycled often. Thus, the degradation is taken into account when providing energy discharging. Eqs. (13) and (14) calculate Vehicle-to-Grid (V2G) discharging degradation cost.

$$soe_{v,t}^{\text{EV}} = soe_{v,t-1}^{\text{EV}} + e_{v,t}^{\text{CH}} \cdot \eta^{\text{CH}} - e_{v,t}^{\text{DCH}} / \eta^{\text{DCH}}$$
$$-E_{v,t}^{\text{RUN}} / \eta^{\text{RUN}} + e_{v,t}^{\text{FCH}} \cdot \eta^{\text{FCH}} \quad \forall v, t \in V, T_{(t \neq 1)}; \qquad (15)$$
$$soe_{v,t}^{\text{EV}} \geq SOE^{\text{MIN}} \cdot CAP_v^{\text{BAT}} \quad \forall v, t \in V, T; \qquad (16)$$
$$soe_{v,t}^{\text{EV}} \leq SOE^{\text{MAX}} \cdot CAP_v^{\text{BAT}} \quad \forall v, t \in V, T; \qquad (17)$$
$$soe_{v,t}^{\text{EV}} \geq SOE^{\text{T0}} \cdot CAP_v^{\text{BAT}} \quad \forall v \in V, h = 24; \qquad (18)$$

Eq. (15) calculates the current SOE based on the SOE from the previous timestep, amounts of charged and discharged energy, energy used for driving (E_RUN) and energy used for fast charging when there is insufficient energy to complete the trip (e_FCH). Eqs. (16) and (17) limit the SOE of a battery to its minimum and maximum capacities, while eq. (18) sets the final SOE to its initial value.

III. Input Data and Case Studies

The simulations are carried out in two stages. The first stage is designed without FCR activation scenarios with day-ahead EV schedules only. This is achieved by neglecting the FCR activation energy in eq. (11), i.e. the amount of activated energy from FCR in the first stage is zero. The second stage is run after the first stage and it embodies the real-time realizations of FCR activation. Ten scenarios of simulated FCR realizations are utilized while the accepted DAM energy and FCR bids from the first stage are held fixed. The simulations are run for one day with half-hour time step, while the DAM and FCR bids are modeled as one-hour products. The model was formulated as linear program in Fico Xpress optimization environment and run on a typical PC.

TABLE I: Electric Vehicle (EV) Type Data

EV Type	Battery Capacity	OBC Rated Power	Battery Price	Fleet Share
Small	20 kWh	3.7 kW	€ 3250	30
Medium	40 kWh	7.4 kW	€ 6500	40
Large	60 kWh	11 kW	€ 9750	30

A. Input data

The data used to model EV behavior is taken from the Joint Research Center European driving study [12], [13], [14], and [15]. Three EV types were modeled and their data is show in Table I. Three slow charging points were modeled with power ratings of 3.7, 7.4 and 11 kW. Fast charging was modeled as 50 kW. DAM and FCR market prices as well as activation data are from the French power system on Nov. 21, 2018 (EPEX and RTE data). This day is specifically chosen as it had the highest volatility of DAM prices within one day in 2018. The activation scenarios are calculated based on probability density functions created from the RTE 2018 data of FCR accepted capacity bids and FCR activated energies using equations:

$$A^{\text{UP\_FCR}} = \frac{\text{Activated UP FCR energy}}{\text{Accepted FCR UP capacity} \cdot DT} \qquad (19)$$
$$A^{\text{DN\_FCR}} = \frac{\text{Activated DN FCR energy}}{\text{Accepted DN FCR capacity} \cdot DT} \qquad (20)$$

Efficiencies used in this paper are as following; slow charging $\eta^{\text{SCH}} = 0.95$, discharging for driving $\eta^{\text{RUN}} = 0.90$, discharging as V2G $\eta^{\text{DCH}} = 0.85$, and fast charging $\eta^{\text{FCH}} = 0.80$. SOE parameters used for all EVs are following: $SOE^{\text{MAX}} = 1$, $SOE^{\text{MIN}} = 0.2$, $SOE^{\text{CV}} = 0.8$, and $SOE^{\text{T0}} = 0.4$. Battery degradation parameters: $D_1^{\text{BAT}} = -0.3429$, $D_2^{\text{BAT}} = 0.03403$, $D_3^{\text{BAT}} = 0.004287$, and $D_4^{\text{BAT}} = 0.008317$.

B. Case Studies

For the same input data seven different charging and FCR product modes are observed:

1) Dumb or uncontrolled charging: EVs immediately charge after the plugging to the charging point and charge until fully charged ;
2) G2V no FCR: unidirectional controllable charging without the possibility of FCR provision,
3) G2V S FCR: unidirectional controllable charging with the possibility of symmetrical FCR provision,
4) G2V A FCR: unidirectional controllable charging with the possibility of asymmetrical FCR provision,
5) V2G no FCR: bidirectional controllable charging without the possibility of FCR provision,
6) V2G S FCR: bidirectional controllable charging with the possibility of symmetrical FCR provision,
7) V2G A FCR: bidirectional controllable charging with the possibility of asymmetrical FCR provision,

TABLE II: Different Charging Modes Results

	Dumb	G2V no FCR	G2V S FCR	G2V A FCR	V2G no FCR	V2G S FCR	V2G A FCR
OF Value	652.75	329.49	267.38	-359.39	175.02	-1030.19	-1201.80
Fleet SOE Mean [%]	63.87	64.29	64.11	76.60	73.06	71.39	67.55
Over SOEmax [#]	0	0	22	3263	0	306	11
Over SOEmax [MWh]	0	0	0.00	3.35	0	0.09	0.00
Under SOEmin [#]	0	0	1790	225	0	1058	2358
Under SOEmin [MWh]	0	0	1.95	0.21	0	1.70	4.75

IV. Results

The acquired results are show in Table II through 6 comparable parameters:

i. OF Value: First stage objective function value in Euros;
ii. SOE Mean [%]: Mean SOE in percent for the whole fleet and through all scenarios,
iii. Over [#]: Number of timesteps when SOE of individual EV exceeds its maximum SOE,
iv. Over [MWh]: Sum of energy in timesteps when SOE of individual EV exceeds its maximum SOE, i.e. the energy which cannot be stored in specific EV as planned one day ahead of delivery,
v. Under [#]: Number of timesteps when SOE of individual EV falls behind its minimum SOE,
vi. Under [#]: Sum of energy in timesteps when SOE of individual EV falls behind its minimum SOE, i.e. energy that cannot be withdrawn from the EV as planned one day before the delivery.

A. Costs and Bids

As displayed in Table II, adding controllability, either through V2G discharging or through FCR provision, decreases overall charging costs of the EV fleet. Unidirectional control without FCR reserve provision splits the total cost in half compared to the dumb charging, while symmetrical FCR provision yields additional 10% in total cost decrease. The overall cost turns to profit in the case of G2V asymmetrical FCR provision.

Cost of V2G without FCR provision is less than a third of the dumb charging cost and around 50% of G2V no FCR cost. Adding FCR provision to V2G charging creates profits for users where asymmetrical provision is identified as the financially most attractive option. V2G A FCR mode yields 3.3 times higher revenue compared to G2V A mode.

Reasons for such OF value distribution through modes *3)*, *4)*, *6)* and *7)* is further illustrated in Figures 1, 2, 3 and 4. The DAM and FCR bids of the EV fleet are shown in sub-figures *a)*. As shown in Figure 1, G2V S mode is heavily constrained and can offer FCR only when DAM charging takes place (only in the morning price valley). G2V A mode is released of the symmetry constraint and can therefore provide continuous FCR down reserve and occasional up reserve while the fleet is charging (Figure 2). Allowing V2G discharging enables (see Figures 3 and 4) continuous up and down FCR provision when the EVs are in the idle status (not charging, discharging or driving). Additional benefit of V2G A mode compared to V2G S mode is more available FCR provision in a fleet's charging/discharging period.

B. Fleet SOE

The mean fleet SOE is around 64% for the first three modes (Table II) and it increases significantly for G2V A FCR mode because provision is asymmetrical and only in the direction of additional charging (up reserve). The three V2G cases are in between the previously mentioned cases since V2G cases keep SOE a bit higher to be able to discharge later in the day, but not as high as the SOE increased during the G2V A FCR case.

The stochastics behind the FCR activation and SOE behaviour are displayed in sub-figures *b)*, which display the mean fleet SOE during the day (measure units in % on the left x axis) and error in the form of difference of the real mean SOE after activation and planned day-ahead mean SOE (measure units in MWh on the right x axis) for all observed scenarios. Since there is only low FCR reservation in the G2V S mode, the SOE deviation is negligible (Fig. 1). On the other hand, G2V A mode provides FCR in only one direction and the error in fleet SOE significantly increases, but the mean SOE value never exceeds the upper SOE limit (Fig. 2). In V2G modes, Figures 3 and 4, the error exist in both directions, depending on how activation unfolds in a specific scenario. The The asymmetrical case, since its activation is not balanced in up and down directions, suffers from slightly more deviations in the fleet SOE.

C. Individual EV SOE

The results tackling the individual EV SOE issues are presented in Table II (last four rows) and subfigures *c)*. Rows *Over SOEmax [#]*/*Under SOEmin [#]* and *Under SOEmin [MWh]* show the number of timesteps when the amount of total energy EVs exceed their SOE maximum or minimum value. It could be concluded that the SOE of individual EVs rarely exceeds their limits in all modes except G2V A FCR mode, which pushes the SOE for quite a number of EVs over the upper SOE bound. Subfigures *c)* display three lines, the upper/lower line shows the EV with highest/lowest SOE in a specific timestep observing all scenarios and the entire fleet. The medium line shows the planned mean day-ahead SOE curve for the entire fleet.

The upper conclusion can be confirmed in subfigures *c)*, where in all figures except Fig. 2 the highest SOE is around SOEmax. In G2V A mode, the highest SOE is mostly above the SOE limit, in some timesteps close to 125%. For the lower

SOE bound, the conclusions are contrary. G2V A FCR mode yields the lowest number of periods when EVs' SOE fall bellow the lower limit (however the number and energy below this threshold is not negligible). G2V S FCR mode provides a very small capacity in the FCR market but EVs whose SOE descend below the minimum threshold is very high, even higher than in the case of V2G S FCR mode. However, when we compare the minimum amount an individual EV SOE reaches in those two modes, Figs. 3 and 1 indicate that in V2G S FCR mode the worst SOE falls below 0%, while in G2V S FCR mode it never falls below 5%.

V2G A FCR mode is the most profitable one, but it is followed by the highest issues when observing the individual EV SOE minimum limits. The total under SOE energy is 2.8 and 2.4 times higher than in G2V S and V2G S modes, respectively.

D. Realized Charging/Discharging of a Fleet

Subfigures *d)* show the amount of total realized charging/discharging energy of the fleet in different scenarios and the maximum energy that can be charged/discharged by the fleet. In both the G2V cases, the charging energy is much lower than its maximum. In V2G cases, during charging/discharging periods, it almost reaches maximum in both directions to retain as much profit as possible from the highest price difference during the day.

V. Conclusion

This paper observes how the individual EV and EV fleet SOE behave during the FCR reserve provision. It can be seen that neglecting the FCR activation during the scheduling process satisfies the SOE boundaries at the fleet level, but leads to infeasible SOE states of individual EVs. This issue can be reinterpreted in the following way: in periods when individual EVs' SOE exceeds/fall bellow its limits, the aggregator would in reality be unable to provide the scheduled reserve and suffer from penalties imposed by the system operator. To solve this issue the EV aggregator should use the intraday market to revert to its scheduled operating point. Additionally, sophisticated re-dispatching algorithms that can activate another EV if the scheduled EV is not able to provide the scheduled service are needed. One of the options is to include the FCR activation stochastics in the day-ahead scheduling algorithm and decrease the number of EVs potentially charging or discharging into infeasible SOE values.

The final conclusion is that the real value of V2G dispatching does not lie in selling energy but in creating as wide as possible capacity for FCR reserve provision.

References

[1] International Energy Agency, "Global EV Outlook 2019," 2019.
[2] European Distribution System Operators for Smart Grids, "Smart charging: integrating a large widespread of electric cars in electricity distribution grids," 2018.
[3] Eurelectric, "Smart Charging – Key to unlocking Electro-mobility's potential," Brussels, 2017.
[4] N. E. Koltsaklis, A. S. Dagoumas, and I. P. Panapakidis, "Impact of the penetration of renewables on flexibility needs," Energy Policy, vol. 109, pp. 360–369, Oct. 2017.
[5] E. Ela, M. Milligan, and B. Kirby, "Operating Reserves and Variable Generation," Cole Boulevard Golden, 2011.
[6] M. MacDonald, "Impact Assessment on European Electricity Balancing Market," Brighton, 2013.
[7] "Frequency Containment Reserve (FCR)." [Online]. Available: https://www.emissions-euets.com/internal-electricity-market-glossary/793-frequency-containment-reserve. [Accessed: 30-Nov-2019].
[8] O. Borne, M. Petit, and Y. Perez, "Net-Present-Value Analysis for Bidirectional EV Chargers Providing Frequency Containment Reserve," in 2018 15th International Conference on the European Energy Market (EEM), 2018, pp. 1–6.
[9] T. Soares, T. Sousa, P. B. Andersen, and P. Pinson, "Optimal Offering Strategy of an EV Aggregator in the Frequency-Controlled Normal Operation Reserve Market," in 2018 15th International Conference on the European Energy Market (EEM), 2018, pp. 1–6.
[10] S. Hashemi, N. B. Arias, P. Bach Andersen, B. Christensen, and C. Traholt, "Frequency Regulation Provision Using Cross-Brand Bidirectional V2G-Enabled Electric Vehicles," in 2018 IEEE International Conference on Smart Energy Grid Engineering (SEGE), 2018, pp. 249–254.
[11] L. Herre, J. Dalton, and L. Soder, "Optimal Day-Ahead Energy and Reserve Bidding Strategy of a Risk-Averse Electric Vehicle Aggregator in the Nordic Market," in 2019 IEEE Milan PowerTech, 2019, pp. 1–6.
[12] "EU Science Hub - European Commission." [Online]. Available: https://ec.europa.eu/jrc/en. [Accessed: 30-Nov-2018].
[13] G. Pasaoglu, D. Fiorello, A. Martino, G. Scarcella, A. Alemanno, A. Zubaryeva, C. Thiel, and L. P. O. of the E. Union, "Driving and parking patterns of European car drivers - a mobility survey" 2012.
[14] C. Thiel, A. Alemanno, G. Scarcella, A. Zubareyeva, and G. Pasaoglu, "Attitude of European car drivers towards electric vehicles: a survey," JRC Rep., p. 28, 2012.
[15] G. Pasaoglu, D. Fiorello, L. Zani, A. Martino, A. Zubaryeva, and C. Thiel, "Projections for Electric Vehicle Load Profiles in Europe Based on Travel Survey Data Contact information", vol. 1. 2013.

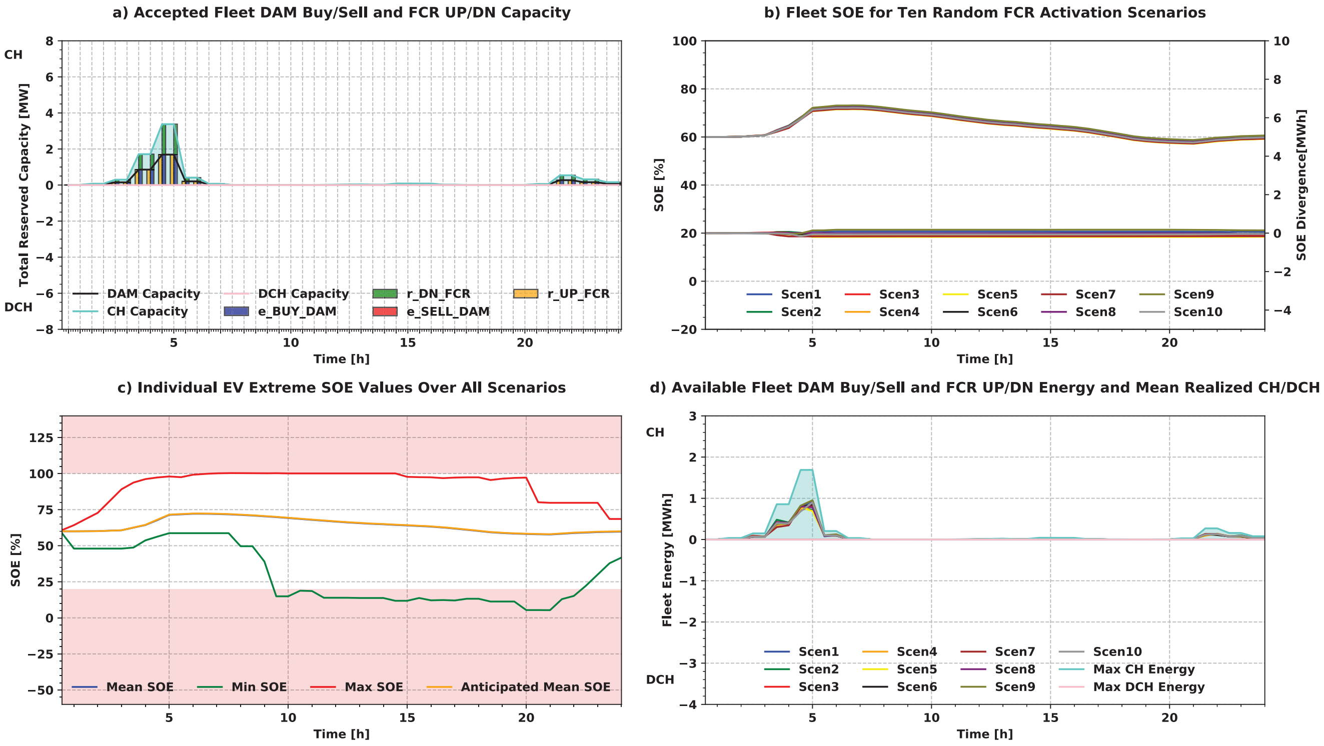

Fig. 1: Results for G2V Symmetric FCR Provision

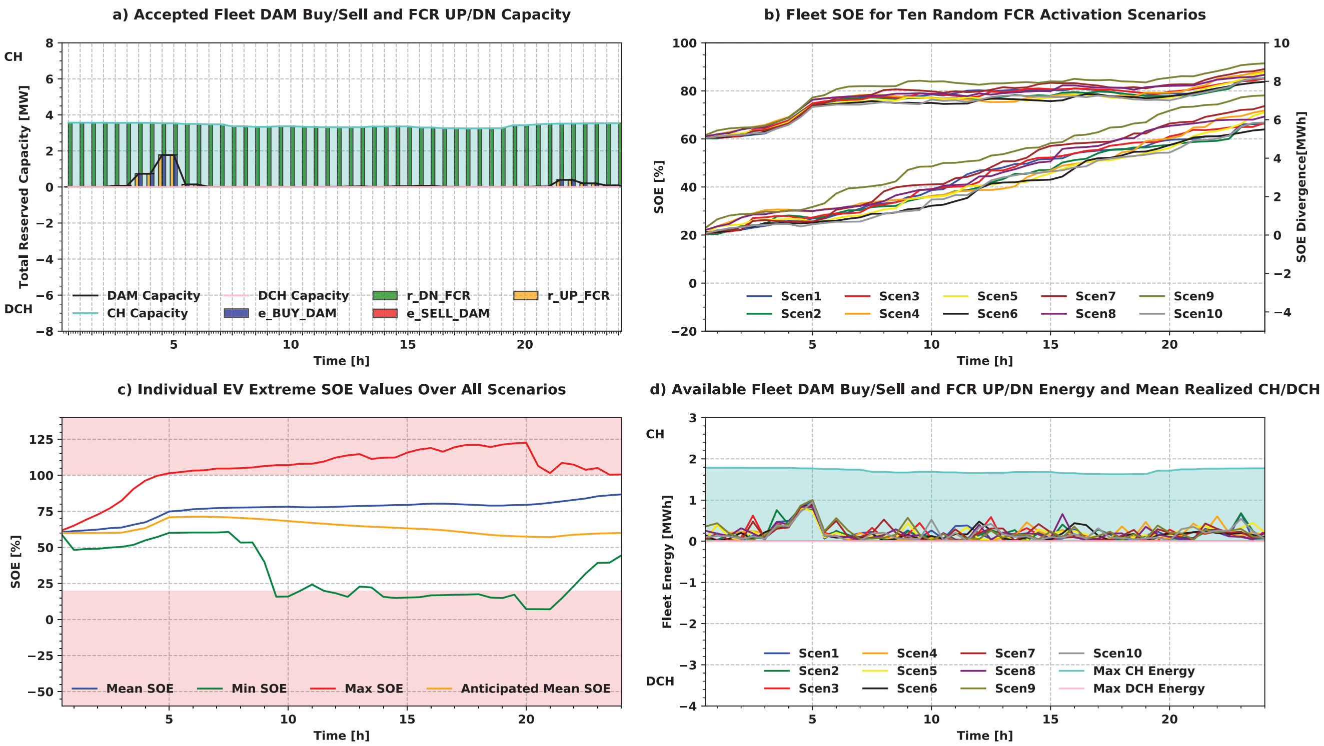

Fig. 2: Results for G2V Asymmetric FCR Provision

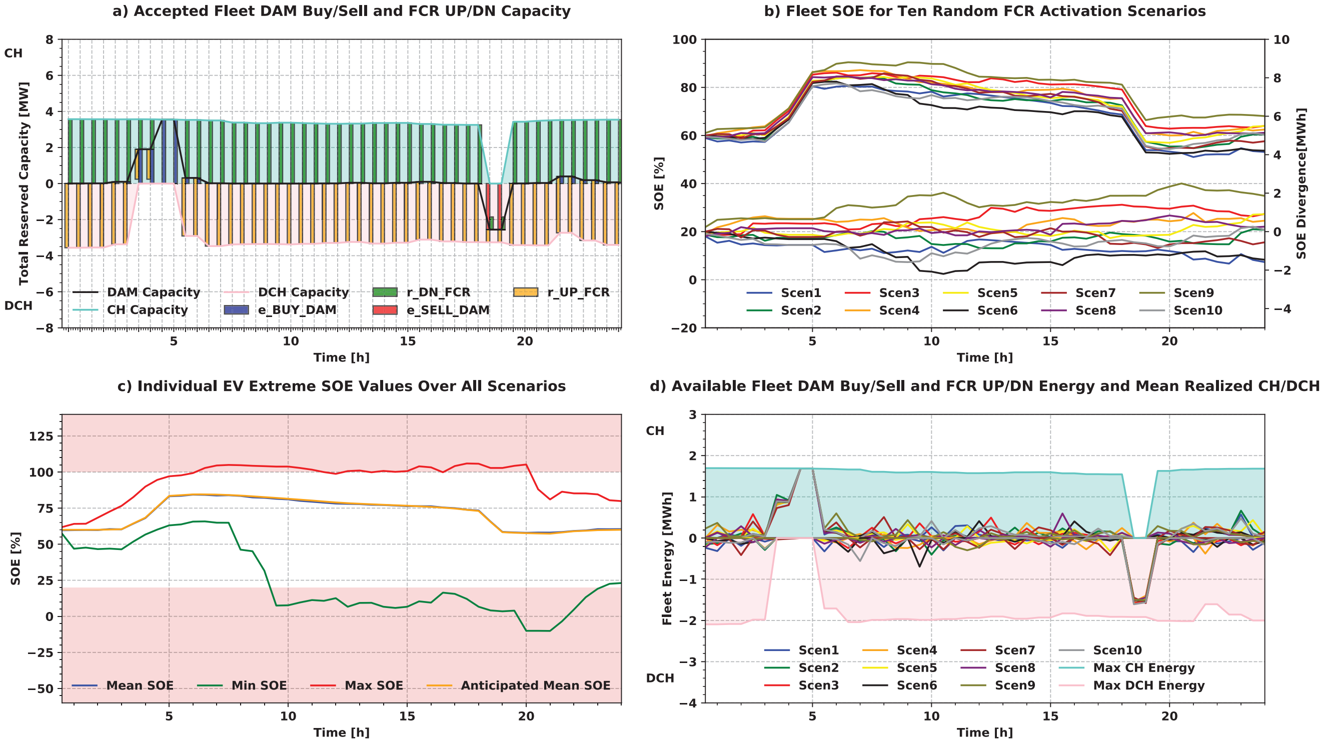

Fig. 3: Results for V2G Symmetric FCR Provision

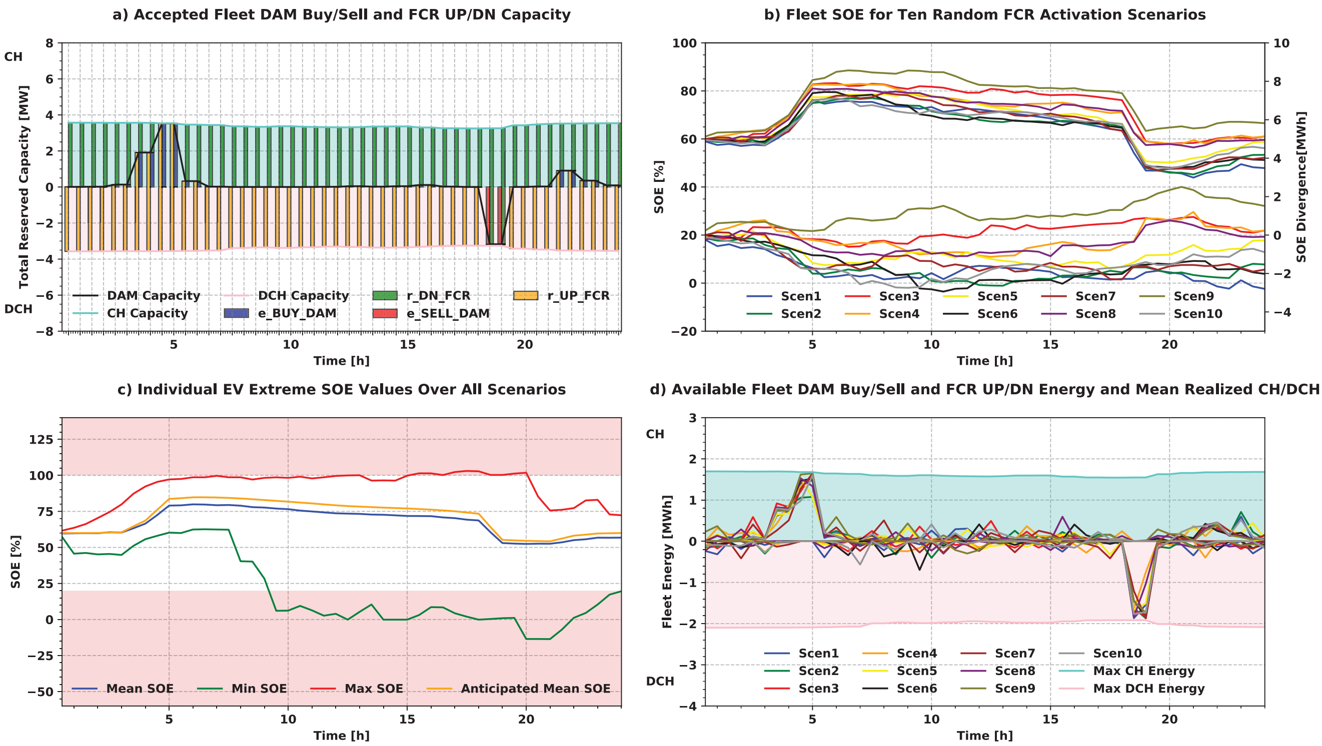

Fig. 4: Results for V2G Asymmetric FCR Provision