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Research Papers

The influence of frequency containment reserve flexibilization on the economics of electric vehicle fleet operation

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ABSTRACT

In recent years, the spot and ancillary service markets have become a relevant source of revenue for stationary battery storage systems. During this period, many markets have become increasingly flexible with shorter service periods and lower minimum power requirements. This flexibility makes the markets attractive for pools of electric vehicles (EVs), providing the opportunity to earn additional revenue. In this paper, multi-year measurement data from 22 commercial EVs are used to develop a simulation model to calculate the available power of an EV pool. In addition, the driving logbooks of >460 vehicles from commercial fleets of 14 different economic sectors are analyzed. Based on our simulations, we discuss the influence of shorter service periods on available pool power and power uncertainty. The key findings are that, especially at times with a high pool power, the uncertainty is low. This leads to the conclusion that commercial fleets offer a highly reliable power profile during known idle times depending on the economic sector. All investigated 14 sectors show high and reliable power availability at night and most show this availability also during weekends while others show a regular driving pattern seven days a week. These results are applicable to any energy market. To have a concrete use case, the impact of frequency containment reserve (FCR) flexibilization on the economics of an EV pool is analyzed using the German FCR market design from 2008 to 2022. It is shown that, depending on the fleet, especially the two recent changes in service periods from one week to one day and from one day to 4 h generate the largest increase in available pool power. Further future reductions in FCR service periods will only produce minor benefits, as idle times are often already longer than service periods. According to our analysis, revenues of about 450 €/a to 750 €/a could have been achieved per EV in the German FCR market between mid-2020 and the first quarter of 2022.

1. Introduction

This section presents the thematic overview, a summary of existing literature on vehicle-to-grid (V2G) concepts with focus on the provision of frequency containment reserve (FCR) through electric vehicles (EVs) and highlights the scientific contribution of this paper. Fig. 1 provides a graphical overview of the paper. First, two databases (EV measurements and driving data) and EV master data are used for the development of a simulation model. The results of the simulation model are power capability profiles, which are the bidirectional power potential of different EV pools. The profiles are used together with historical FCR price data within a calculator to estimate FCR revenues for different market designs. We show that commercial fleets are generally capable of offering V2G services with a predictable uncertainty depending on day and time. Possible future flexibilization in form of shorter service periods will have only little impact on the available power compared to the current service periods of 4 h.

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1.1. Motivation and contribution

The increasing integration of volatile renewable energy generation and flexible energy storage has led to an increasing flexibilization of spot and grid service markets in recent years. The term flexibilization refers on the one hand to the reduction of service periods for the respective market and on the other hand to the introduction of the required minimum power bids to participate in the market. Battery storage systems (BSSs), in particular stationary large-scale BSSs, already have a significant share of the global market for FCR. From this market, they continue to displace conventional market participants such as large power plants. In Germany, the share of stationary large-scale BSSs in the FCR market was about two thirds in 2021 [1–3]. However, these BSS have the problem that they are refinanced exclusively from FCR revenue. The ensuing price competition in order to win a contract in the bidding process has led to a 50 % decrease in FCR prices from 2015 to 2020 and made the market increasingly unattractive as the main application for these large-scale BSSs [1]. For this reason, so-called multi-use concepts for BSSs are a promising way of generating revenue from various applications [4]. Decentralized BSSs can participate in virtual power plants at times when they do not fulfill their primary use. Such a pool can consist of BSSs of all types and includes stationary as well as mobile BSSs in the form of EVs. EVs, in particular, have a great potential of free battery capacities that are not used for mobility due to idle times of >95 % [5,6]. Especially commercially operated EVs often have short and regular (and thus plannable) distances and driving patterns that allow the provision of grid services [7]. Therefore, the increasing flexibility of the FCR market (decrease of minimum power bid from 5 MW to 1 MW and shortening of service periods from one month to 4 h in recent years) makes this market attractive for the fluctuating power of EVs in multi-use concepts. This paper analyses the influence of FCR flexibilization on the profitability of commercially operated EVs in the use case of the German market design, which should be representative for a large region of Central Europe, since the FCR market of Germany, Belgium, the Netherlands, France, Switzerland, and Austria is coupled and the price varies only slightly between the countries [8]. Even though there is a variety of scientific publications on FCR and EVs, none of the literature focuses on the recent and possible future FCR flexibilization and its impact on the economics of EV fleets potential in this market. While other publications focus mainly on optimized operation strategies and multi-use in a fixed market design, this paper analyzes the influence that the market changes themselves have on the economics of an EV fleet. Further, it quantifies the power uncertainty that different economic sectors have, which can be used by aggregators for all energy markets. This analysis has so far not been examined (see Section 1.2). We contribute with our paper to fill this gap. The key research questions answered are:

1. How much FCR power can commercial EV fleets offer over different time periods? (Section 3.1)
2. What power uncertainty can be expected during different time slots due to mobility (Section 3.1)?
3. What would be the effect of further reductions in FCR service periods on the economics of EV fleets (Section 3.2)?
4. How much money can EVs expect to earn through FCR? (Section 3.3)

1.2. Literature review and differentiation

There are many publications on the provision of frequency regulation by stationary BSSs or EVs, each with a different focus and data. We divide our literature research into the areas (1) provision of FCR using BSSs and combination of applications (see Table 1), (2) simulation and optimization of frequency regulation using EVs (see Table 2), (3) demonstrations, experiments, and field tests of frequency regulation using EVs (see both Appendix, Tables 9 and 10), and (4) generation of revenues using fleets of EVs for the provision of frequency regulation. We classify the sources according to Table 1 into respective focal points, which we discuss individually in the following.

(1) The provision of FCR with large-scale BSSs has been investigated and shown to be possibly profitable, depending on the energy-to-power ratio (EPR) and specific market conditions [9–11]. Especially the so-called "30-min" criterion when providing FCR with batteries in the German regulatory market had been determined as a crucial burden for providers [10,11]. This criterion required that the maximum offered bidirectional FCR power must be able to be provided for at least 30 min at any time within the respective service period. In 2019, the German federal network agency (FNA) obliged the transmission system operators (TSOs) to apply the 15-min criterion instead of the 30-min criterion for BSSs making the market more attractive to batteries due to smaller EPRs (see Section 2.6) [12]. Multi-use, the combination of different storage applications, has been studied for years [4,13–16]. The main results of these studies are that the combination of different storage products increases the economic attractiveness, but that there are regulatory hurdles to overcome [13–15]. In this context, Englberger et al. published an open-source tool simulating multi-use including an economical and a technical analysis [16]. However, all mentioned publications

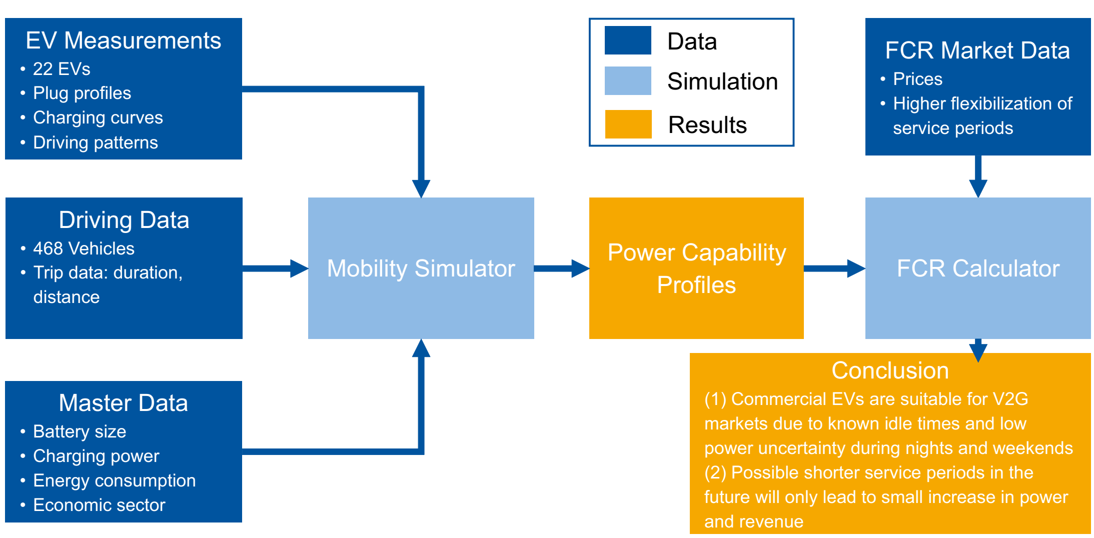

Fig. 1. Graphical abstract.

Table 1
Summary of selected literature of the provision of FCR using BSSs and multi-use.

	Source	Date	Focus	Results
FCR	Fleer et al. [9]	2016	Economics of the provision of FCR using BSS based on two case studies considering FCR prices and battery aging	- BSS only profitable with a power-to-energy ratio of 1:1, not with 1:2 - Decreasing battery prices will increase possible profit but could lead to lower achievable revenues due to market saturation
FCR	Zeh et al. [10]	2016	An optimal control algorithm for the operation of FCR with BSS is developed for the market conditions of 2015	- FCR Market conditions for BSS of August 2015 (30-min-criterion) lead to unprofitable operation
FCR	Thien et al. [11]	2017	Operation strategy for an installed 5-MW-BSS providing FCR is developed and influencing parameters are analyzed	- Benefits could be enhanced having better market conditions such as 15-min instead of 30-min-criterion
Multi-use	Fitzgerald et al. [13]	2015	Evaluation of different services BSS can provide in the US market including a meta-study and analysis of barriers	- Combination of applications increase the economic value - Despite technical readiness, regulatory hurdles exist that prevent an economically profitable use of BSS
Multi-use	Stephan et al. [14]	2016	Analysis of investment attractiveness of different single applications of BSS and their combination by developing a techno-economic model	- Combination of applications improves the investment attractiveness - Market barriers often prevent the combination of applications
Multi-use	Braeuer et al. [15]	2019	Evaluation of economics of BSS installed in German small and medium sized enterprises when combining applications of peak-shaving, FCR and arbitrage	- Individual applications are not profitable, but combination of applications are - Influence of arbitrage application is small
Multi-use	Englberger et al. [16]	2020	Simulation of energy storage systems serving multiple applications including an analysis of technical and economical parameters	- Application stacking more economical than single use - Publication of open-source tool which combines BSS applications

Table 2
Summary of literature about simulation and optimization of the provision of frequency regulation using EV fleets.

Source	Date	Focus	Results
Tomić et al. [19]	2007	Analysis of two fleets of utility EV providing power for regulation services in the US.	- V2G enables potential revenue streams for EV owner in most ancillary service markets
Han et al. [23]	2010	Proposition of an aggregator pooling EV to provide frequency regulation	- Development of an optimal control strategy for EV fleet considering battery energy capacity and desired final SOC for driving purpose
Sortomme et al. [20]	2012	Development of a V2G algorithm for the scheduling of the provision of the ancillary services load regulation and spinning reserves in US markets	- Algorithm combines several ancillary services - Simulations show that even though there are challenges, providing ancillary services can provide benefit for the owner, the aggregator and the grid.
Bessa et al. [24]	2012	Optimized bidding of EV fleet in day-ahead and secondary reserve Iberian market.	- Using an aggregator to optimize the bidding of energy decreases charging costs - Variables like the electricity price and the maximum available power in each time interval need to be forecasted
Codani [25]	2015	Simulation of participation of 200,000 EV in FCR market in France	- Potential revenue higher with bidirectional charging compared to unidirectional charging - A high number of EV might saturate FCR market
Hoogvliet et al. [21]	2017	Economic analysis of the potential revenue EV owners can raise when providing regulating power in the Netherlands	- Depending on EV type and driving pattern an EV owner can raise 120 € to 750 € per year when providing regulating and reserve power - Provision will lead to higher battery energy throughputs (11 % to 55 %)
David et al. [22]	2017	Economic analysis of the provision of frequency regulation using EV considering battery degradation and driving requirements	- EV with highest battery capacity lead to the greatest economic benefit, as the cyclic degradation is lowest - Major constraint is the power capability of the EV and the chargers - Incentives should be developed to convince EV owners to provide frequency regulation

focus on stationary applications and do not evaluate the flexibilization of the FCR market, on which this paper focuses.

(2) The concept of Vehicle-to-Grid (V2G) was first introduced by Kempton et al. [17,18]. Since then, the concept has been studied extensively. Table 2 provides publications, in which the provision of FCR with EVs has been simulated and optimized. The provision of different frequency regulation products by EVs offers economic potential for the owner and the aggregator [19–22]. Furthermore, the grid can benefit from it [20]. Moreover, control algorithms for aggregators have been developed and bidding strategies optimized [23,24]. V2G can be carried out using unidirectional and bidirectional chargers. Despite their momentarily higher purchase costs, bidirectional chargers offer higher economic potential [25]. In addition, simulations show that the energy throughput is increased by the provision of frequency regulation, which might lead to increased battery degradation [21,22]. However, none of the mentioned publications evaluate the impact of recent and possible future FCR flexibilization as this paper does. Further, the power uncertainty was not quantified before.

The concept of **second-life use** means that after years of use for mobility, vehicle batteries are removed from EVs and integrated into other applications like stationary BSSs in order to provide grid services or trade energy [26–28]. However, batteries contained in EVs can also be used to provide these V2G services within their first life, if they are temporarily not required for their primary use, namely mobility. We therefore call this concept **"dual use"**.

(3) Several demonstration projects have been and are being carried out to investigate the provision of frequency regulation with EVs. Appendix, Table 9, gives a selection of such projects, while Appendix, Table 10, lists scientific publications done within these projects. In 2002, the first project on frequency regulation supply with EVs was implemented in California [29,30]. It showed that EVs are capable of providing frequency regulation to the grid. The German INEES project ran from 2012 to 2015 and analyzed the

provision of secondary control reserve with an EV fleet of 20 V2G-compatible vehicles [31,32]. The provision proved to be technically possible, but not profitable under the conditions prevailing at the time [31]. In addition, the impact on the distribution grid in terms of power quality and manageability was not assessed as negative [32]. Another demonstration project ran from 2013 to 2018 in California, within which 29 bidirectional EVs provided frequency regulation [33,34]. Among other things, optimization models were used to minimize operating costs and maximize revenue from ancillary services [34]. The so-called "Parker" project, within which many scientific findings were published, ran from 2016 to 2019 in Denmark [35–41]. The scientists showed that FCR supply is possible with unidirectional charging stations, but is economically much more attractive with bidirectional charging stations [36,37,40]. Furthermore, it was found that the response times and accuracies of the charge controllers are sufficient to provide control power [37,38]. Nevertheless, communication delays and measurement errors turned out to be practical obstacles [39]. Factors influencing the economic benefit of providing control power are the availability of vehicles, the charging efficiency and the operation strategy used [39–41]. In addition, an industrial project ran between 2018 and 2019 in which the provision of frequency regulation with a prequalified EV was successfully tested in Germany [42]. Another project, monitored by the German research institution FfE (Forschungsstelle für Energiewirtschaft e.V.), started in 2019 and analyses use-cases of EVs in different electricity markets [43]. To analyze the interaction between EVs, charging infrastructure and the grid, 50 EVs will be tested in the field [43,44]. The interconnection of EVs to a virtual power plant providing frequency regulation will be investigated in another industrial project until 2021 [45,46]. However, these projects focused on the demonstrations of V2G applications and did not focus on the market side as this paper does.

(4) Different publications have taken a look at the possible revenues that pools of EVs can generate when providing FCR. As early as 2005, Kempton and Tomic estimated the possible annual revenues for the provision of frequency regulation using a Toyota RAV4 to reach $ 4928 [5]. In 2019, Thingvad et al. analyzed the economic value of EV reserve provision in Northern Europe [40]. Assuming a power availability of 10 kW, the possible annual revenues resulted to 1395 €. One year later, Bañol Arias et al. published an analysis of the economic benefits for EV owners when participating in primary frequency regulation markets [41]. Their resulting profits (costs were subtracted from revenues) ranged between 100 € and 1100 € per EV and year. In 2021, Thingvad et al. published another paper about the provision of frequency regulation with EVs [47]. In this work, they published battery degradation data about EVs which had provided primary frequency regulation over a period of five years. Moreover, they calculated the revenues the EVs had generated. Including battery degradation costs and conversion losses and neglecting investment and maintenance costs, Thingvad et al. estimated a yearly profit of 751 €. Later in 2021, in Tepe et al. we published a work combining pools of EVs in an optimal manner [48]. In doing so, we estimated a yearly revenue per EV of 378 € in the German FCR market in 2020. However, none publication focused either on the influence of flexibilization nor power uncertainty of EV pools.

The most important project (without focus on FCR) for this paper, "GO-ELK", was conducted by the Institute for Power Generation and Storage Systems at RWTH Aachen University [49]. Within this project, 22 commercially operated EVs were equipped with data loggers to measure quantities such as battery voltage and battery currents during charge and trips. The logged data build the basis of many of the results shown in this paper.

2. Methodology

This section describes the paper's methodology. It presents the used data, the developed driving profile generator, the modelling approach, and the market for FCR in Germany.

2.1. Data collection

This paper uses two databases containing the driving data of commercial vehicles. Table 3 compares the most important data of both databases and gives further information on calculations and assumptions.

2.1.1. Database "Measurements"

The first database, "Measurements", was created by the Institute of Power Generation and Storage Systems (PGS) at RWTH University. The high-resolution data ($T = 1$ s) of commercially operated electric vehicles were measured between 2013 and 2016 within the project "Commercially operated electric vehicle fleets (GO-ELK)" [49]. In the project, four fleets of EVs were deployed in different sectors over a period of 30 months [49]. During their use, vehicle data (driving, charging and battery data) of the total of 22 EVs were recorded by data loggers in the vehicles and the charging stations. For a detailed description of data collection and adjustment, please refer to [49–52]. The values include battery voltage, battery current, start and end of a trip, distance travelled, consumption, and the location at the end of the trip. Further, the measurements were used to create charging curves as an input for the model (see Section 2.4).

2.1.2. Database "Logbooks"

The second database, "Logbooks", was included within the project REM 2030 (regional eco mobility). The project was supervised among others by the Fraunhofer Institute for Systems and Innovation Research ISI and various institutes of the Karlsruhe Institute of Technology (KIT) and covered different topics of future urban mobility [53]. The goals were new innovative traffic concepts of individual mobility in order to avoid local emissions [53]. Within this project, Fraunhofer ISI collected travel data of commercial vehicles, which can be used free of charge for non-commercial purposes. The database contains over 91,000 journeys of 630 vehicles of different trades. We filtered the database so that only vehicles with a minimum number of one trip and a minimum logging duration of one week were considered. The vehicles are classified according to their economic sector (NACE criteria) [54]. The KIT classified the vehicles used from database "Logbook" into 15 economic sectors. Within the economic sector, there are further definitions of vehicle classes. The values include start and end of a trip, the distance travelled, and the location at the end of the trip.

The database "Logbooks" contains only vehicles with internal combustion engines. In order to model these as fully electric vehicles, the unrecorded consumption and the plug and unplug behavior must be estimated.

To estimate the consumption, the values shown in Appendix, Table 8, are used. These result from various studies, test results and manufacturer data sheets of EVs that are in the same vehicle class as the internal combustion engine vehicles. The average consumptions of the listed EVs range from 18 kWh/100 km and 27 kWh/100 km depending on the vehicle class [55]. To determine the consumption of the EVs in kWh per 100 km of a trip, the consumption is distributed normally around the average consumption of the vehicle class (expected value: average consumption of all EVs in Appendix, Table 8, and variance: 1 kWh / 100 km). This way, the effect of the temperature on the consumption is also statistically taken into account.

To estimate the plug and unplug behavior, the information on the location is used, which is given as the distance to the company site. Whenever the distance symbolizes that the car is parked at the company site, it is assumed to be plugged. Therefore, the assumption is made that every EV has an available charging point.

Table 3
Available data in the two databases used in this paper.

	Category	Database "Measurements" (22 cars)	Database "Logbooks" (468 of 630 cars)
Vehicle Data	Product	see Appendix, Table 7 (e.g. Smart ED, Renault Zoe)	see Appendix, Table 8
	Vehicle class	small to medium	see Appendix, Table 8
	Type of vehicle drive	electrical drive	combustion drive
	Industry / trade	see Appendix, Table 7 (e.g. healthcare and energy provider)	see Appendix, Table 8
	Environment	urban and rural	urban and rural
Trip Data	Start of trip	timestamp	timestamp
	End of trip	timestamp	timestamp
	Trip consumption in kWh	~15 to 25 kWh/100 km	18 to 27 kWh/100 km (see Appendix, Table 8)
	Trip distance	measured in km	measured in km
	Distance to company at trip end	taken from charge events	measured with GPS
Battery Data	Max. charge power in kW	3.7 kW to 22 kW (AC)	according to "Measurements"
	Battery energy in kWh	16 kWh to 24 kWh	19.1 kWh to 80.7 kWh (see Table 8)
	Charging curve	measured in laboratory	according to "Measurements"
	Start of charging	measured timestamp	according to "Measurements"
	End of charging	measured timestamp	according to "Measurements"
Charging Station Data	Charge power	1.8 kW (single phase AC) to 11 kW (three phase AC)	according to "Measurements"

2.1.3. Combination of the two databases

For the combination of the datasets, the different data formats were unified and merged. For unification, driving profiles were created as both datasets contain start and end of a trip, distance travelled, and consumption (see Sections 2.2 and 2.3). These driving profiles are the input for the model described in Section 2.4. To merge the databases, the EVs from database "Measurements" were divided into the respective economic sectors and supplement the large KIT data set according to Appendix, Table 8. With 94 vehicles, the manufacturing sector has the largest number of vehicles, especially of the vehicle class "medium" (see Appendix, Fig. 23 (left)). This is followed by public administration (71 vehicles) and healthcare service (58 vehicles), in which mainly small vehicles are used. Some clusters follow with 30–40 vehicles and there are also four clusters with <10 vehicles each. This should be considered when looking at the results, as the power capability profiles in these cases are only based on small sample sizes. The average duration of data recording for most clusters is about 20 days (see Appendix, Fig. 23 (right)). The analyses of our database "Measurements" (data recording periods of more than one year) show that these relatively short durations are already sufficient to reliably map daily operations in the examined sectors.

2.2. Statistical analysis

In the following, we present a short statistical evaluation of the data used. For better comprehensibility, we present the healthcare service as an example from database "Measurements". This fleet shows the same driving pattern for the whole week, which makes the daily analysis done very representative. Further analyses on database "Logbook" indicate in general similar results as the evaluation done for the "Measurement" database. All vehicles of the two databases were evaluated analogously to the evaluations presented in this section. However, as this paper does not represent a mobility study, no further evaluations are made at this point and reference is made to mobility studies such as [56–59].

Fig. 2 shows the three events "plug & charge", "end of charge", and "unplug" of the Smart ED of a healthcare service. The health-care service runs in two shifts a day: 50 % of all unplug events are at around 7 a.m., which is the start of the first shift. It ends at around noon and the cars are plugged and charged. The second shift runs from around 2 p.m. to 9 p. m., which is again indicated by the "plug and charge events".

The average distance (see Fig. 3) between two charging operations is about 40 km, although the maximum possible distance range of the vehicle is around 100 km. Further, the average duration between unplug und plug is about 8 h (see Fig. 4). All travel durations above about 8 h can be assigned to shifts after which no charging process is initiated. This is the case for about 30 % of all trips. The regular charging with 11 kW charging stations at the end of the shifts leads usually to a fully charged vehicle a short time after returning. While the average SOC after return is around 60 %, this value is often 100 % or near to 100 % when

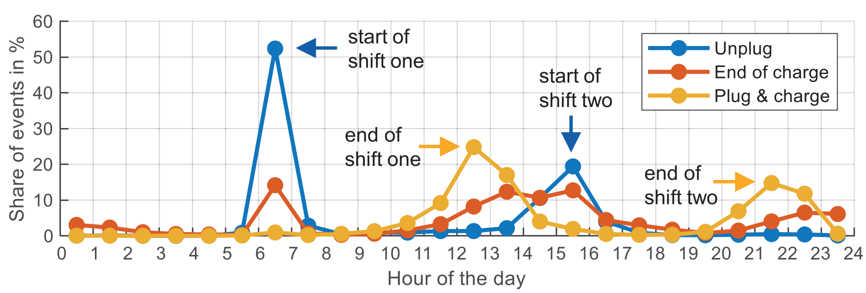

Fig. 2. Trip events of EVs in healthcare service (908 measured trips from database "Measurements").

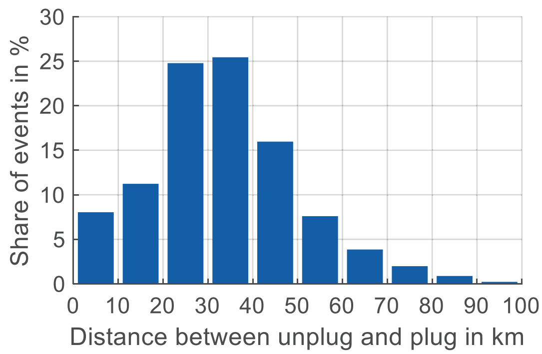

Fig. 3. Distance between unplug and plug (908 measured trips of EVs in healthcare service from database "Measurements").

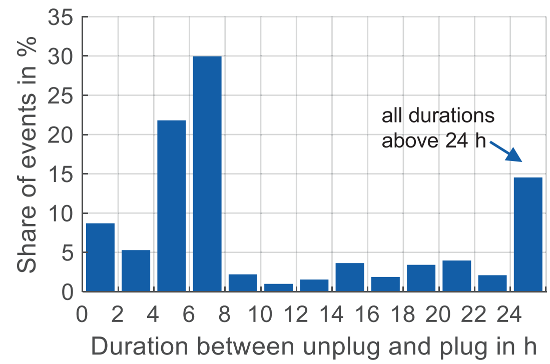

Fig. 4. Duration between unplug and plug (908 measured trips of EVs in healthcare service from database "Measurements").

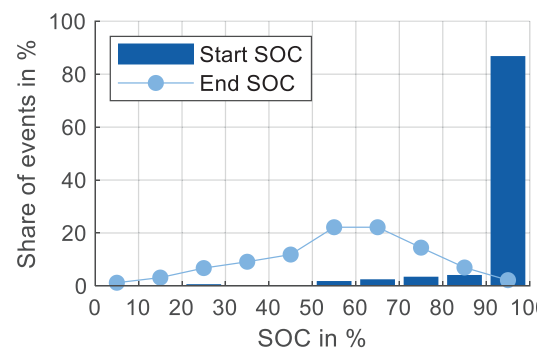

Fig. 5. SOC at unplug and plug (908 measured trips of EVs in healthcare service from database "Measurements").

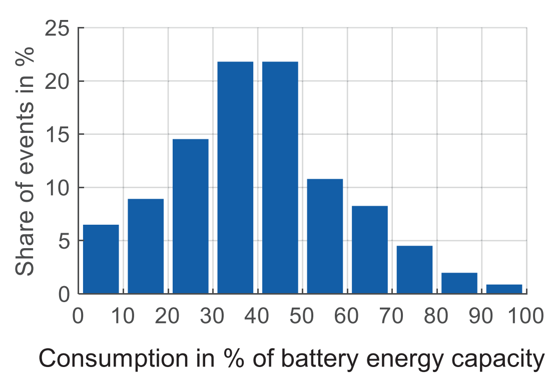

Fig. 6. Consumption between unplug and plug (908 measured trips of EVs in healthcare service from database "Measurements").

the vehicle starts a trip (see Fig. 5). The unplug events where the EV is not fully charged in the morning are mainly due to software issues with the internal SOC estimation showing values slightly below 100 % although the EV does not charge any more. The small amounts of needed energy underline the potential of free capacity ranges shown in recent literature (see Section 1.2). Due to the relatively short distances, the vehicle consumes on average only 40 % to 50 % of the battery energy capacity (see Fig. 6). The measurements also contain different consumptions as a function of the temperature as the EVs were measured over two years and thus within different seasons (a low temperature leads to high consumptions and vice versa).

2.3. Driving profiles

The statistical analysis is now used to generate driving profiles such as the probability of a trip start or day and time dependent distributions of distances, durations, and energy consumptions. The data is presented for a Smart ED that was part of the healthcare service fleet in the statistical analyses shown in Section 2.2.

The trip-start probability w_{start} of a plugged vehicle is calculated as a function of day and time. To get the trip-start probability, the number of unplug events are divided by the total number of days, when the car was connected to the charging station (see Eq. (1) and nomenclature in Appendix, Table 6).

$$w_{start}(t) = \frac{\sum_{n=1}^{N} trip_{start,n}(t)}{N}$$
$$with\ trip_{start,n}(t) = \begin{cases} 1, & if\ trip\ started\ on\ day\ n\ at\ time\ t \\ 0, & otherwise \end{cases} \quad (1)$$
$$with\ N = number\ of\ days, where\ EV\ was\ plugged$$

The trip-start probabilities are exemplarily shown in Fig. 7. The probability for starting a trip is over 60 % for the first shift and is most likely between 6 a.m. and 7 a.m. During the second shift, with cumulated probability values of approx. 40 %, the number of unplugs is slightly lower. Outside the shifts, the probability of plugging out from the charging station with values below 10 % is relatively low. Further, the trip distances (Fig. 8), durations (Fig. 9), and normalized consumptions are sorted by day and time to ensure a realistic driving behavior of the analyzed vehicles. The figures show the probabilities and distribution clustered for 1 h for clearer presentation. The resolution used for simulations is 15 min and thus higher (see Section 2).

The value distributions presented, such as distance, duration, and consumption, are also evaluated as a function of time, resulting in separate distributions for each point in time. The distances driven and the durations between plug and unplug are subject to temporal fluctuations. Both, the longest distances and durations are the start of each trip of the two shifts in the healthcare service. Especially if the EV is not plugged after the end of the first shift, the distances and durations get longer as their values also cover the second shift and vice versa.

2.4. Modelling

The generated profiles are the input for an implemented mobility model. The model simulates the driving behavior and the grid

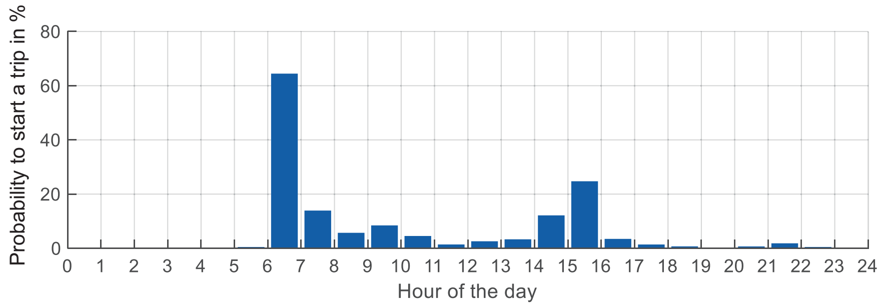

Fig. 7. Trip-start probability (Smart ED, healthcare service).

connection of EVs via the charging station. Fig. 10 presents the general structure of the simulation:

- If a vehicle begins a trip due to the calculated probability, it gets random but correlated values of the day and time-dependent distributions of distance, duration, and the normalized consumption per kilometer. The new EV data are updated with the given trip values and the car is plugged to the charging station after the given trip duration.
- If a vehicle does not begin a trip, it charges in case the state-of-energy (SOE) is lower than the required energy for the mobility. This is explained in more detail in the following Section 2.5.

The charging process of the vehicle is simulated with real charging curves measured in our laboratory at PGS RWTH Aachen University. Fig. 11 (left) depicts an 11 kW constant-power charge. The AC power on the grid side is larger than the DC power on the EV battery side, which shows the power losses due to the power converter. The efficiencies are around 93 % for the constant power phase and decrease during the power decline. Battery current and voltage are shown in Fig. 11 (right). The current values range in the case of this charge (11 kW) from 2 A to approximately 30 A at battery voltages of around 320 V to 390 V. During the constant power phase, current decreases while voltage increases with higher SOE. It is important to consider that at around 90 % SOE the constant-power charge turns into a constant-voltage phase resulting in a strong decline of current and power. When offering ancillary services, EVs with - in this case - SOEs above 90 % are therefore not chosen to participate in the pool because of their strong decline in power. That is why a charging SOE limit of the EV is implemented in the simulation. This limit is set dynamically and ensures that all logged trips could have been done, individually for each EV. The charging limit is mostly around 80 % of the SOE and is further explained in Section 2.5.

For the simulation, it is assumed that the EVs are solely charged at the company site and that all EVs have an available bidirectional charging point.

2.5. Virtual sectioning of the battery

The primary use of an EV is mobility. However, several studies as well as our presented data have shown that the average trip distance is quite low resulting in a low average energy needed for most trips. Thus, there are free energy capacities during most times that can be used for dual-use concepts in order to increase the economics of operation. Within these concepts, the primary use should not be limited by the secondary use. For dual use, the battery must be virtually divided into the energy range for primary use (mobility energy $E_{mobility}$) and the energy range for secondary use (marketable energy E_{market}), as shown in Fig. 12. The mobility energy must be ensured at any time in order to undertake the regular trips of the vehicle. It consists of a reserved minimum energy for spontaneous trips at any time and a trip energy within certain time windows, when the vehicles are general, is the difference of the total battery energy E_{Bat} and the current mobility energy as shown in Eq. (2). It is a derived quantity that describes how much of

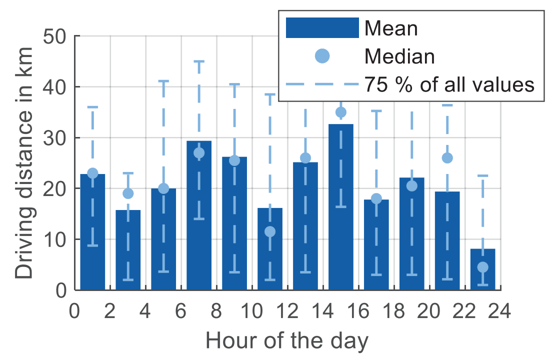

Fig. 8. Distance distributions as a function of the departure time (Smart ED, healthcare service).

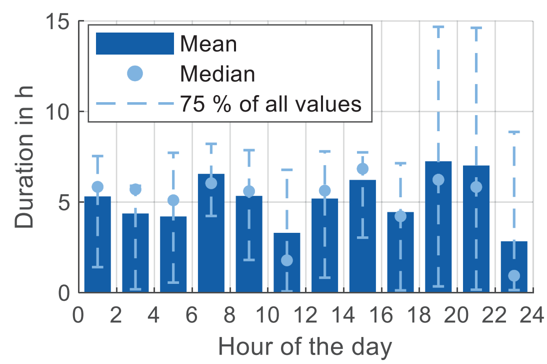

Fig. 9. Duration distributions as a function of the departure time (Smart ED, healthcare service).

the battery's rated energy capacity a user would allow to use for a secondary use such as FCR.

$$E_{market}(t) = E_{Bat} - E_{mobility}(t) \tag{2}$$

Based on the state of energy (SOE), the marketable energy can be divided into the charge energy E_{charge} and the discharge energy $E_{discharge}$ as shown in Eqs. (3)–(5) and in Fig. 12 (left).

$$E_{market}(t) = E_{charge}(t) + E_{discharge}(t) \tag{3}$$

$$E_{charge}(t) = E_{Bat} - SOE(t) \ \forall \ SOE(t) > E_{mobility}(t) \tag{4}$$

$$E_{discharge}(t) = SOE(t) - E_{mobility}(t) \ \forall \ SOE(t) > E_{mobility}(t) \tag{5}$$

In order to calculate the FCR power an EV can provide, some basic calculations are necessary that are described in the following. Generally, the FCR power can either be restricted by:

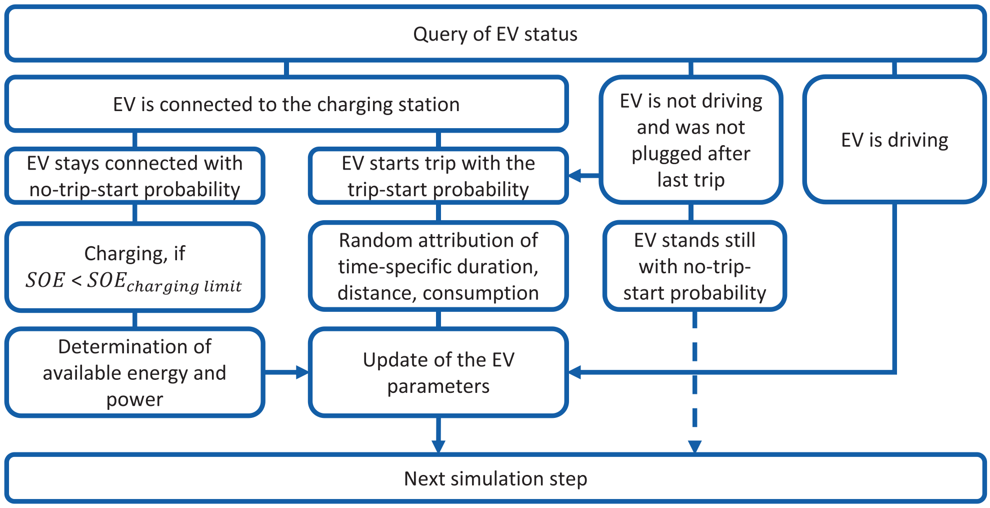

Fig. 10. Simulation flow of the implemented mobility model.

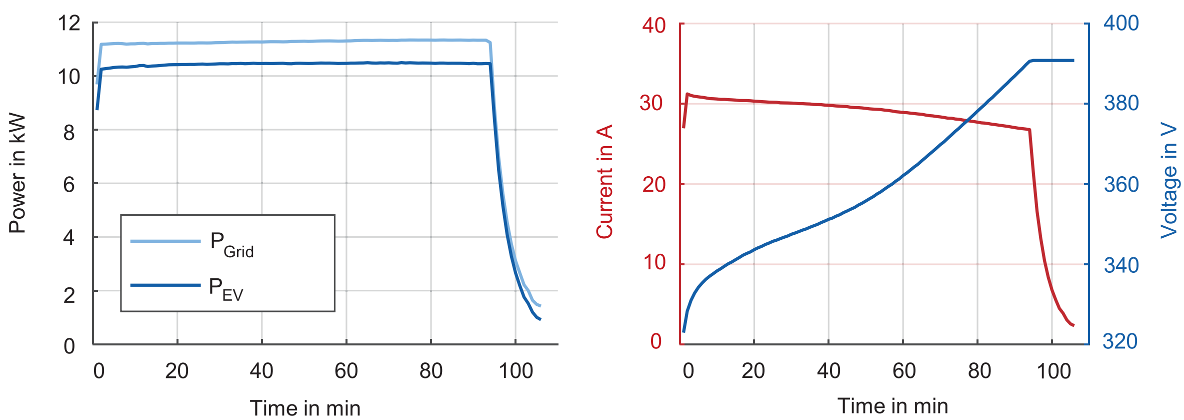

Fig. 11. Measured grid and battery power (left) and battery current and voltage (right) of a Smart ED during charge at 11 kW AC power.

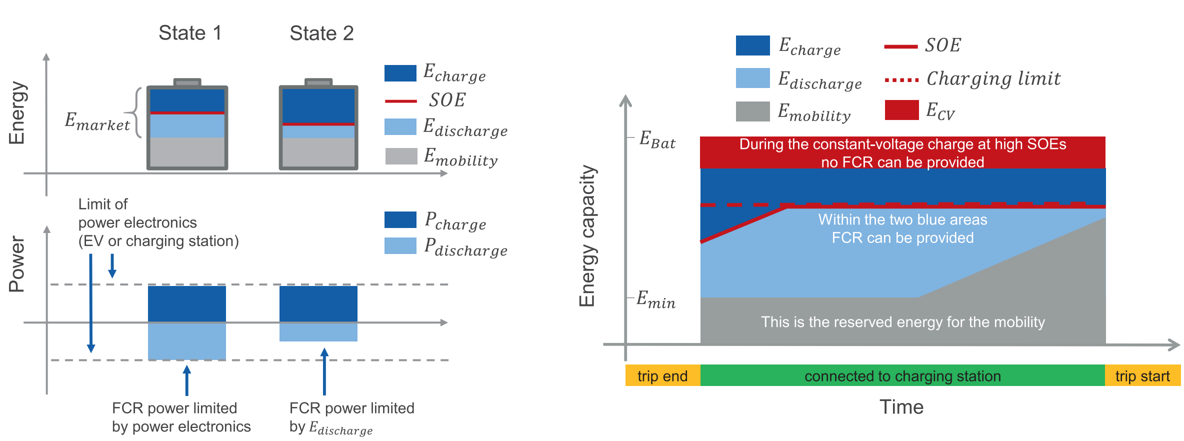

Fig. 12. Virtual division of the battery energy capacity and calculation of available power. Left: static. Right: time-dependent in the case of EVs. Inspired by [31].

1. the rated power P_{EV} of the battery converter of the EV,
2. the rated power P_{CS} of the charging station, or
3. the charge or discharge energy in combination with the time of power supply.

Eqs. (6) and (7) consider all three cases for calculating the available charge power P_{charge} and discharge power $P_{discharge}$ taking the service period ΔT_{supply} of the required 15 min full FCR power into account.

$$P_{charge}(t) = min\left\{\frac{E_{charge}(t)}{\Delta T_{supply}}; P_{EV}; P_{CS}\right\} \quad (6)$$

$$P_{discharge}(t) = min\left\{\frac{E_{discharge}(t)}{\Delta T_{supply}}; P_{EV}; P_{CS}\right\} \quad (7)$$

Example. Assumptions for calculating the charge power:
E_{Bat} = 50 kWh (before constant voltage phase starts).
$E_{mobility} = 15\ kWh$ (30 % of E_{Bat}); SOE = 30 kWh.
$P_{EV} = 11\ kW$; $P_{CS} = 22\ kW$, $\Delta T_{supply} = 15$ min $= 0.25\ h$.
Calculation:
E_{charge} = 50 kWh – 30 kWh = 20 kWh

$$P_{charge} = min\left\{\frac{20\ kWh}{0.25\ h}; 11\ kW; 22\ kW\right\}$$

$$= min\{80\ kW; 11\ kW; 22\ kW\}$$

= 11 kW (power limited by EV in this case)

For our simulation, we assume a bidirectional charging station. Although most of the current charging stations at the time this paper is submitted are unidirectional, broad literature expects EVs to play an important role in ancillary services of the future and bidirectional charging stations will probably emerge for V2G and vehicle-to-home (V2H) applications (see Section 1.2). However, many car manufacturers still do not provide any internal vehicle information such as the SOE to the charging station and prohibit the charge control as they use older Open Charge Point Protocols (OCPP version 1.5 or 1.6). Nevertheless, protocols like OCPP version 2.0 with the corresponding ISO 15118 protocol as well as the CHAdeMO protocol send information and allow charge and discharge control.

The required energy for mobility changes with the time of day and the day of the week depending on the use profile of the EV (see Fig. 12). In order to take the individual use profile of the EVs into account, the minimum energy required is calculated on the basis of historical journey data. In addition, a spontaneous mobility buffer of at least 30 % of the battery energy is implemented. This value is specified by users in a field test as the desired minimum for spontaneous trips [31]. Whenever the SOE is above the mobility energy, the vehicle can provide grid services as long as the SOE is not within the E_{CV}, where the constant-voltage charging phase takes place (see Fig. 11). In order to provide flexibility in charging and discharging the EV, an additional individual charge limit of about 80 % SOE is introduced (see Fig. 12 (right)). This upper limit is chosen as high enough that sufficient energy for all historical journeys is available. The individual charging limit ensures that the single EV is not yet in the constant-voltage phase of the charging process. If the energy for a trip exceeds the 80 %, the charging limit is not applied and the EV is charged to 100 % and cannot participate in FCR during this time.

Table 4
Frequency containment reserve market before July 2019, after July 2019 and after July 2020 [64,65].

	Before July 2019	July 2019 – July 2020	Since July 2020
Direction	Positive and negative power together		
Minimal bid	1 MW		
Minimal increment	1 MW		
Reaction time	30 s		
Provision time	15 min		
Remuneration	Pay-as-bid for power	Market-clearing-price for power	
Time sectioning	1 week	24 h	4 h
Tendering	Tuesdays, 3 pm	D-2, 3 pm,	D-1, 8 am
Demand Germany	551 MW - 620 MW	620 MW	573 MW

2.6. Frequency containment reserve

This section presents the German FCR market design, its requirements for BSSs and the development of FCR prices.

2.6.1. The German FCR market

The frequency regulation is divided into frequency containment reserve (FCR, former primary control reserve), automatic frequency restoration reserve (aFRR, former secondary control reserve), and manual frequency restoration reserve (mFRR, former tertiary control reserve). The three types of frequency regulation have different activation times and replace each other consecutively as shown in Fig. 13. Within 30 s after a frequency deviation of >10 mHz, FCR units in Continental Europe Synchronous Area have to provide FCR automatically [60,61]. This way the frequency drop (respectively rise) is supposed to be stopped. Providers of FCR must offer both positive and negative FCR power for the same service period. It is important to notice that other regions such as the Nordic Balancing Markets [62] or the UK [63] also have faster frequency regulation markets.

The regulatory requirements for FCR varied during the last years as shown in Table 4. Appendix, Table 11, provides the decisions taken on FCR by the German Federal Network Agency (FNA) and the TSOs. Until mid-2011, FCR was tendered on a monthly basis in a pay-as-bid auction, which means that the supplier of FCR had to provide the service for one month continuously and the paid prices were the individual prices that providers bid in the auction [65,66]. From mid-2011 until July 2019, FCR was tendered weekly in a pay-as-bid auction [64,65] and the minimum bid size was decreased from 5 MW to 1 MW [65].

In July 2019, the service period was shortened to one day [65] and the pricing was modified to a market-clearing-price procedure for the offered power [64]. This means that every provider of FCR earns the price of the highest offer that is accepted for the respective bidding period. As a last modification, in July 2020, the service period was made even more flexible to six daily slots of 4 h each [64]. The EU had demanded this higher flexibility and short-term nature of FCR tenders [67].

2.6.2. Requirements on BSS and virtual power plants when participating in the FCR market

BSS are technically able to provide frequency regulation due to their fast reaction times and high cycle stability, which is required when, for example, offering FCR [10,68,69]. In 2015, the German TSOs had decided on a 30-min-criterion for BSS, when providing FCR [70]. As the storages had to provide the positive and negative power simultaneously over the period of one week, the TSOs wanted the BSSs (or pools of BSSs) to be able to provide the awarded power for at least 30 min (instead of the usual 15 min) [70]. Only when BSSs were added to an existing pool to increase its flexibility, 15 min were sufficient [70]. In 2019, the

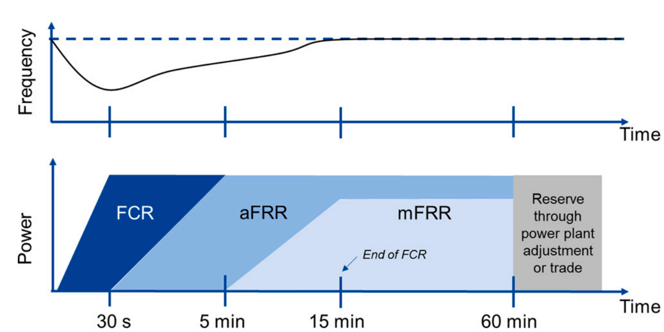

Fig. 13. Division of frequency regulation with exemplary frequency curve (top) and power type responsibilities (bottom) based on [60]. Figure shows only a frequency drop, although FCR is bidirectional.

German FNA rejected this request of the TSOs as it would have discriminated the BSSs operators [12]. In addition to this minimum required amount of energy, an FCR provider must also maintain an additional quarter of its prequalified power as a buffer [71]. This is to ensure that storage management activities can be provided at the same time as FCR provision. For example, a pool of EVs that wants to provide 3 MW of FCR power must have at least (3 MW • 1.25 =) 3.75 MW available. For a pool, the TSOs set a minimum size of 25 kW for the smallest plants and 2 MW for the pool [72]. A system may only participate in one pool at a time [72].

2.6.3. Development of the prices for FCR

Fig. 14 (left) shows the development of the FCR prices from 2008 to 2022. It contains all special features of the market history: the different service periods are marked by different colors. In addition, the range of values of 100 % of all prices shows that the monthly and weekly service periods still had a pay-as-bid price in contrast to the market-clearing price of the daily and four-hourly service periods. The FCR prices show volatility over the shown time period. Nevertheless, a clear trend towards falling prices can be seen from 2015 to the beginning of 2021. While prices in 2015 still averaged around 3600 €/MW/week (peaks above 6000 €/MW/week), by the beginning of 2021 they had fallen to <1500 €/MW/week. This was mainly due to the strong competition in the FCR market caused by the increasing number of large-scale BSSs [2]. However, from mid-2021 prices increased sharply to values in the range of 2000 €/MW/week to 4000 €/MW/week and spiked by the end of 2021 with prices of over 9000 €/MW/week. In 2022 the prices ranged from 2000 €/MW/week to 6000 €/MW/week. Therefore, the FCR prices followed the price development of all other energy markets. Further price developments stay unclear due to unpredictable situations like political tensions around Russian gas supply and the war in Ukraine.

Fig. 14 (right) shows the price ranges for different time spans of the four market designs. The prices for the monthly tendering were significantly higher than for other periods with a mean price of 3486 €/MW/week. While the prices averaged around 2585 €/MW/week during weekly service periods, the mean price during daily service periods was around 1281 €/MW/week and during the service period of 4 h 2531 €/MW/week.

3. Results

In this section the results are presented and discussed. First, the influence of flexibilization on the available power of an EV pool is examined. Subsequently, these results are used to calculate the revenue using the example of German FCR prices. These prices are representative for many countries in Central Europe.

3.1. Available power and uncertainty

As the EVs are on trips for several parts of the day, the available pool power fluctuates. Fig. 15 shows the distributions of the minimum bidirectional pool power of two exemplary clusters ((1) healthcare service care and (2) energy supply) for the current FCR market design of a service period of 4 h. In the following, the minimum bidirectional pool power is called *"power capability profile"*. The distribution shows all days of the year over a period of one week. While the median is represented by the thick line, the differently colored areas show the respective ranges of 50 %, 75 %, and 100 % of all values.

The two clusters are chosen as they are quite representative for the others. While the cluster energy supply shows a pattern that is different for the days Mon-Fri and Sat-Sun, the cluster healthcare service shows nearly the same pattern seven days a week although the power is higher at the weekend. The median power of the energy supply cluster ranges from around 40 % of the pool power during day to around 90 % during night and the weekend. The median power of the healthcare service cluster ranges from about 25 % during day to 80 % at night.

The power uncertainty is defined as the difference of the maximum and the minimum power within a certain time period. The two profiles both show a higher uncertainty during day than during night. Further, the energy supply cluster has only very small uncertainty values of a few percentage points during the weekends.

Fig. 16 shows the median power and the uncertainty for all 14 clusters. The following insights can be drawn from the analysis:

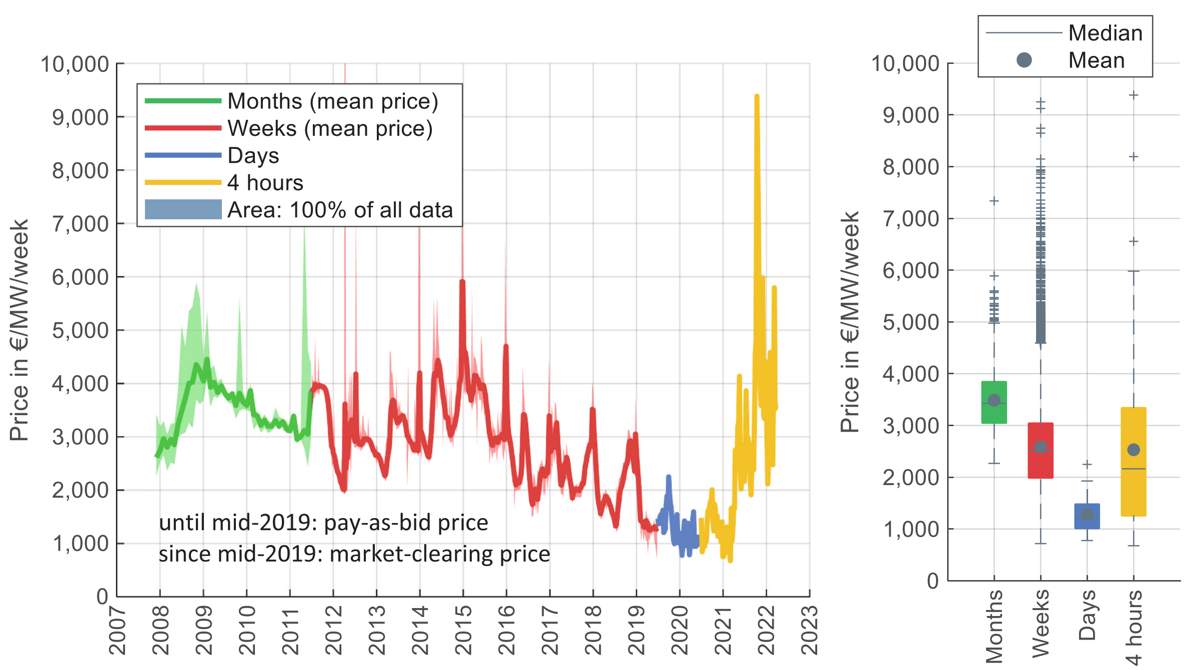

Fig. 14. Left: FCR price development per week until March 2022. Analyzed data from [8]. The prices of the periods of one month, one day and 4 h are scaled to a weekly price for comparability. Therefore, the monthly prices are divided by four, and the daily and four-hourly prices are summed up within the respective week. Right: FCR price ranges for each market design. Analyzed data from [8].

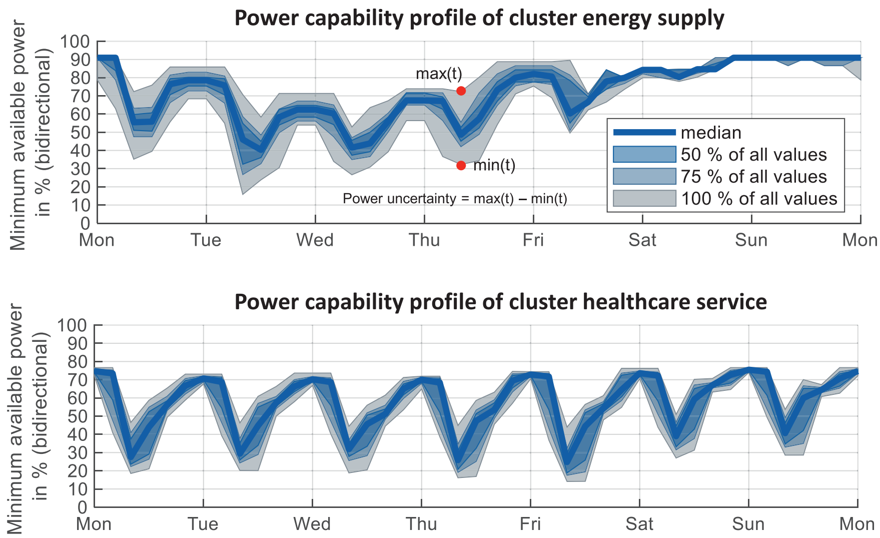

Fig. 15. Power capability profiles of the two clusters energy supply (top) and healthcare service (bottom) for all weekdays in the current FCR market design (service period of 4 h).

- Most clusters show either a clear difference between the days Mon-Fri and Sat-Sun (like the energy supply cluster, referred to as profile type A), or a similar pattern seven days a week (like the healthcare service cluster, referred to as profile type B).
- The median power is with values of around 70 %–80 % of the pool power higher during night than during day (around 40 %–50 %) for both A and B. Further, for the A profiles, the weekends show the highest median powers during the weekend with values around 90 %.
- The uncertainties and the median power have a negative correlation: Especially during the day, there are increased uncertainties around 40 % (up to 80 %). However, during night and weekends, the uncertainties are rather small with values often below 20 % as some vehicles are seldom or not driven at all during these times.
- The profiles already show that EVs are particularly suitable for short periods of ancillary services, as the availability of power varies greatly with the time.

3.2. The influence of FCR flexibilization on available power

Based on the time series of the power capability profiles, the influence of FCR flexibilization can be further investigated. The minimum power within a service period represents the available FCR power. Fig. 17 illustrates the impact of different service periods using the healthcare service power capability profile for an exemplary week. While the absolute minimum of the week determines the FCR power to be marketed in the case of a service period of one week, shorter service periods allow the fleet to be used even at times when many vehicles are connected to the charging stations and can provide power. The power minimum of the weekly service period is <20 % of the pool power. Since the EVs in this case drive about the same seven days a week, the flexibilization from weekly to daily service periods provides on five days (Mon-Fri) only a slight increase in the daily minimum to about 25 % of power. On weekends, slightly fewer trips by the pool EVs provide a minimum above 30 %. The FCR power at the service period of 4 h can follow the volatile profile much better and even corresponds to the

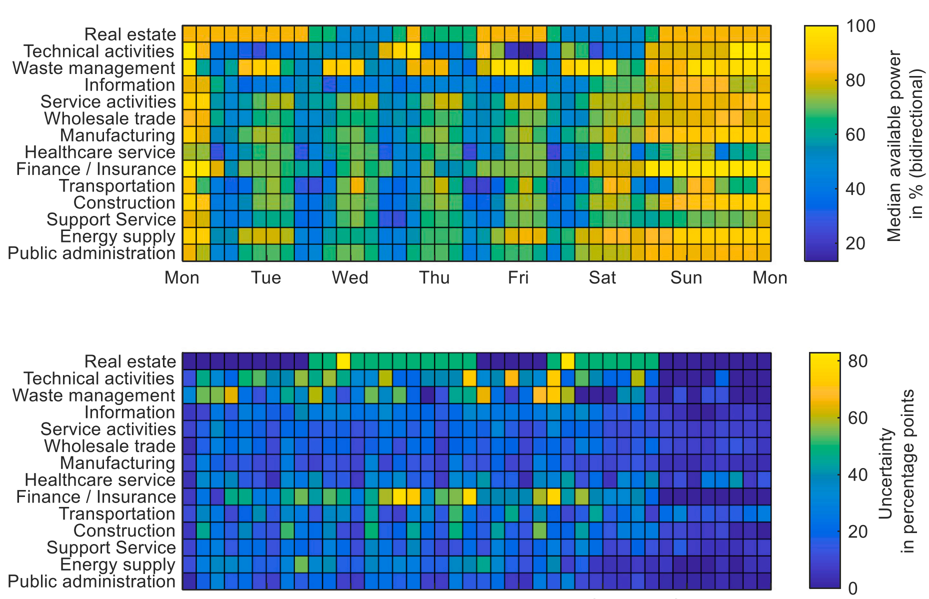

Fig. 16. Median available pool power (top) and uncertainty (bottom) of the EV operating in the chosen sectors.

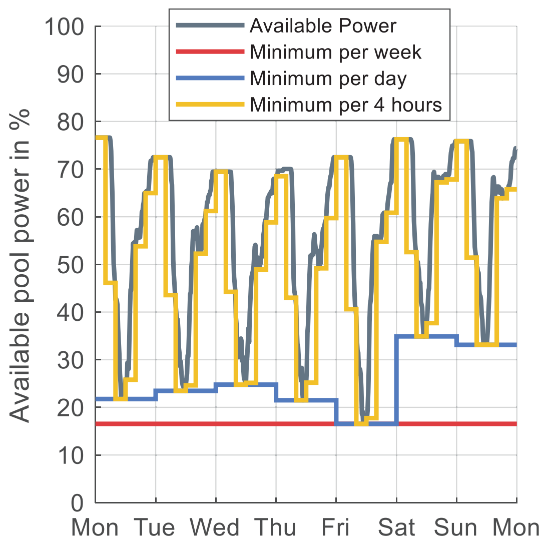

Fig. 17. Available pool power for different service periods for healthcare service cluster.

available pool power of 70 % to 80 % at night. At these times, the available power does not correspond to 100 %, since the vehicles are often not plugged overnight.

Fig. 18 aggregates these evaluations for a whole year and shows the ranges of available power within the year. The influence of the service period on the available power is shown exemplarily for the two clusters discussed before. In total, there are four “real” service periods of the historical and current FCR market designs (1 month, 1 week, 1 day, 4 h) and two fictitious shorter service periods of 1 h and 15 min respectively. The two performance periods of one month and one week are very similar and the available power values are close to the absolute minimum. This is because such long periods often result in a situation where many vehicles are on the road at some point. For this reason, the respective clusters can only offer little power to be able to guarantee service even under worst-case conditions. In such cases, a pool would have to be significantly oversized.

The change from weekly to daily service periods leads for the cluster energy supply already to significantly more time slices at which high powers can be offered. These are especially the weekends, where the cars do not drive that often. However, this change has significantly less effect on the available power of the healthcare service. This is because it operates nearly the same seven days a week and a service period of one day does therefore not bring much improvement. Nevertheless, if the service period is further reduced to 4 h, the power that can be offered by the healthcare service cluster also increases significantly. This increase is particularly due to the night when most of the EVs are connected to a charging station. Since the idle times are usually longer than 4 h, the further flexibilization through the 1-h and 15-min delivery periods will only result in slight increases in the available power for both clusters. The increase in power thus shows a decreasing sensitivity to the shortening of the performance period.

Fig. 19 shows the discussed flexibilization in form of shorter service periods for all 14 clusters. It becomes obvious for all clusters that it is either the change in service periods from weeks to days, the change from days to 4 h, or a combination of both which brings the highest increase in mean power. Depending on the profile, the increase in mean power at these two levels of flexibilization ranges from around 10 percentage points to 35 percentage points. The further shortening of the service time, on the other hand, has only a minor influence on the mean power to be offered. While the change from 4 h to 1 h still leads to an average increase of 4.6 percentage points, this value is only 1.4 percentage points for the change from 1 h to 15 min.

This means for the future that the revenue will mainly depend on the evolution of the FCR price, as further flexibilization of the market will only have a minor impact on the power that can be offered.

3.3. Achievable revenue

This section examines the development of the theoretical revenue of a 1000 EV pool with a charging power of 11 kW per EV.

Fig. 20 shows an example of the power capability profile for the healthcare service and the FCR price for a day in 2020 with a service period of 4 h. The following steps are taken to calculate the revenues. It becomes obvious that the FCR potential of the pool is limited both by the required buffer power (step 2) and the increment condition (step 3).

1. Determination of the minimum power in the respective service period.
2. Division of the minimum power by factor 1.25 in order to ensure the required 25 % power buffer.

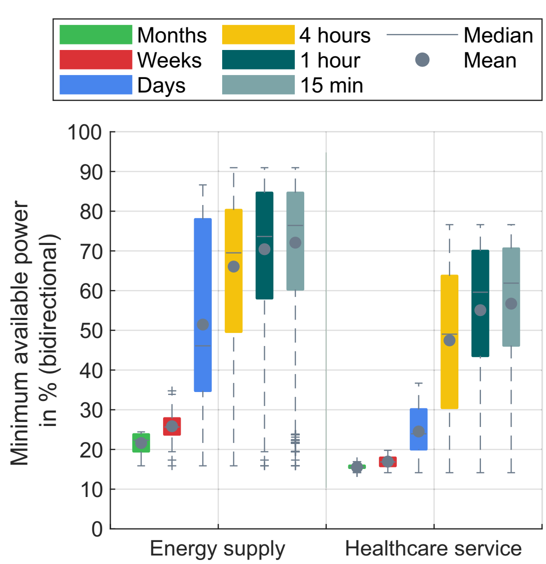

Fig. 18. Available pool power of the EV operating in the chosen sectors over one year.

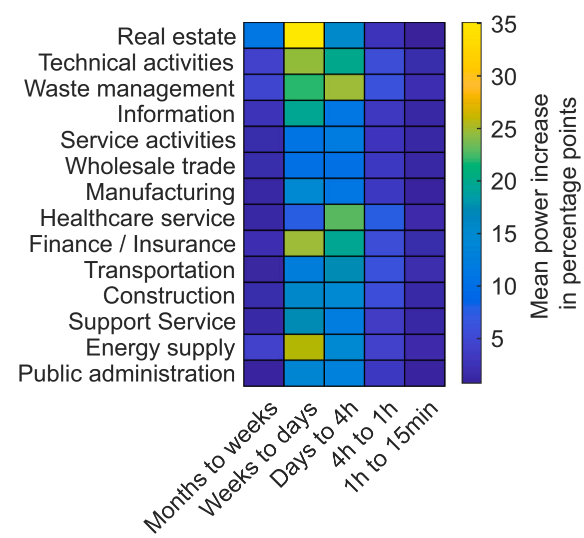

Fig. 19. The influence of flexibilization in form of shorter service periods on the mean power increase.

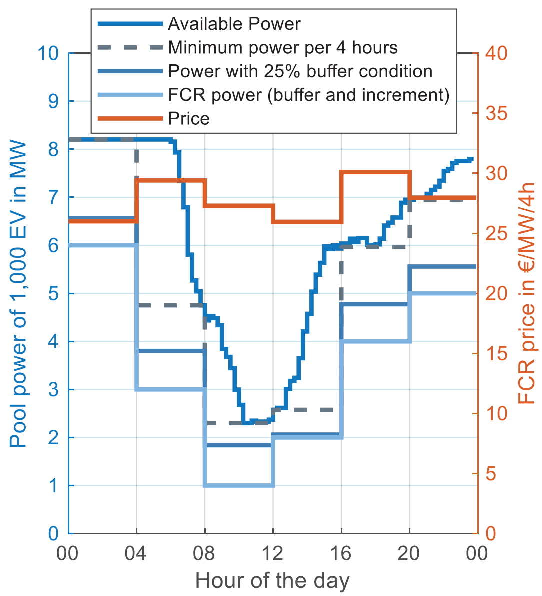

Fig. 20. Available pool power (with buffer and increment condition) and FCR price over one day (cluster: healthcare service).

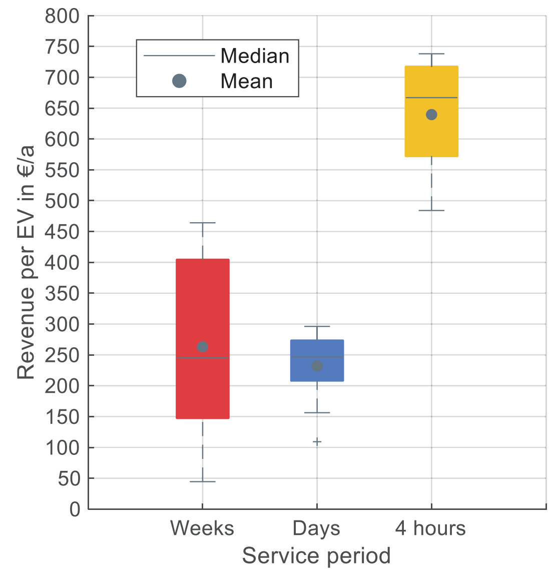

Fig. 21. Mean yearly revenue per EV based on simulation of 1000 EVs over the whole time of service period. Each box plot contains the mean of the 14 clusters.

3. Rounding down the power rest to an integer multiple of 1 MW to correspond to the minimum power of 1 MW and the increment of 1 MW in the current market design.
4. Multiplying the time-dependent FCR power by the time-dependent FCR price to determine revenues.
5. Summation of the revenues for the entire period and normalization to one week.

This procedure is performed for the whole time series of the annual simulations (in the case of the service period of 4 h the simulation is half a year) of all clusters for the three selected service periods of one week, one day and 4 h with historical prices.

Fig. 21 shows the results of the revenue per pool for the last service periods. The plot shows the achievable revenue per EV and year for all clusters based on an annual simulation of a 1000 EV pool for each cluster. Each box plot contains the 14 clusters for the different service periods. It can be seen that the revenues increase on average. The average revenue per EV increases from 263 €/a with weekly service periods, over 232 €/a (daily service period) up to 640 €/a with four-hourly service periods. Furthermore, the overall influence of flexibilization and falling prices clearly depends on the individual service profile as can be examined even more clearly in Fig. 22:

- The change from weekly to daily service periods was accompanied by increasing flexibility and falling FCR prices. For the majority of the clusters the increased flexibility did not overcompensate the falling prices with mean revenue decreases of 31 €/a and maximum decreases of around 180 €/a per EV. However, there are also some clusters for which the flexibilization dominated and their pool revenue increased by up to 136 €/a.
- The change from daily to four-hourly service periods was accompanied by increasing flexibility and increasing FCR prices. Both developments lead to an increase in revenues from 340 €/a to 500 €/a (mean: 408 €/a) per EV. In this case, volatile profiles that differ from day to day could benefit both from offering higher FCR power as well as from increasing prices.
- The overall change from weekly to four-hourly service periods was accompanied by increasing flexibility and nearly a constant mean FCR. The flexibility overcompensates for the falling prices significantly with mean revenue increases per EV of around 380 €/a. Especially the revenue for pool profiles that have a volatile profile within a day such as the healthcare service cluster increased by up to 581 €/a per EV. These profiles can now use, for example, the night hours during which idle times are longer than the service periods of 4 h (see Fig. 17).

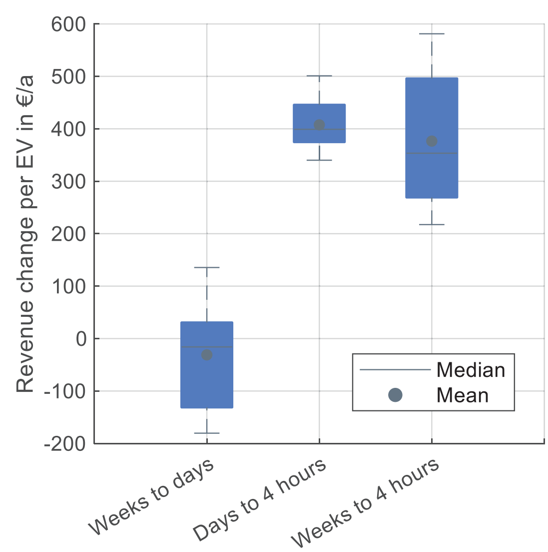

Fig. 22. Change in weekly revenues per EV based on simulation of 1000 EV pool over the whole time of service period. Each box plot contains the 14 clusters.

A detailed overview of the single sectors is given in Appendix, Fig. 24. We have also published an analysis that looks in more detail at the potential of each economic sector and vehicle size [73].

4. Discussion

In this paper, we estimated the revenue potential of EV fleets using historic market prices, mobility profiles of different fleets, and EV characteristics such as the battery size, charging power, and consumption. However, a few points need to be considered for further classification of the results. These relate to techno-economic points and aspects of the charging strategies.

4.1. Techno-economic aspects

In our study, we focused on achievable revenues. These revenues are necessarily offset by associated costs. The costs are mainly composed of hardware and transaction.

For the provision of FCR, a bidirectional charger for the EV is needed. Although, as of the beginning of 2022, most EVs are not used for bidirectional activities yet, but this situation could change quickly. Volkswagen, for example, announced that their EVs will have bidirectional features from 2022 onwards [74]. First bidirectional products for private car owners supporting both standards (CHAdeMO or ISO 15118) already exist [75] (around 6000 € per 7,4 kW wallbox [76]) and they will most likely become cheaper with a growing market.

Besides hardware, there are also operational expenditures such as metering costs, costs for pool management by an aggregator, and battery degradation due to increased battery cycling through FCR (around 250 equivalent full cycles per year for large-scale BSSs [1,69]). The battery degradation costs of two field projects are estimated to be 50 €/a – 100 €/a in [31] and 86 €/a in [47]. Further, the degradation is mainly influenced by calendar aging and not by cycle aging through V2G [47]. The only known source to the authors dealing with operational costs for EV dual use is the INEES project [31], in which the provision of aFRR through EVs was analyzed. The cost estimation for metering, communication, and battery degradation summed up to 700 € to 750 € per year for 2016 and is projected to be 110 € to 350 € per year for a future scenario with bidirectional EV and charging stations. Comparing the possible revenue with the operational costs as of 2022, the profit could probably be around a couple of 100 € per year. This estimate fits well to reported real-world income of 21 € per month (252 €/a) in 2019 for the most earning private EV providing balancing power in the Netherlands for the company Jedlix BV [77]. All in all, the profits can possibly be in low positive ranges, if capital expenditures are neglected. However, this best-case scenario implies that the aggregator is always awarded a contract in the FCR tendering, which is rather unlikely with the growing number of batteries in the market, especially in the future. Besides these costs, high penalties and exclusion of the FCR market could occur, if FCR power cannot be provided in case an unforeseen high number of EVs is on the road. Aggregators should therefore have either absolutely plannable vehicle fleets such as busses or more reliable assets such as stationary BSSs or other power plants in their portfolio.

4.2. Charging strategies and “degrees of freedom”

We assumed that the EVs are plugged whenever they are at the company site and that every EV has an available bidirectional charging station. In case people do not plug the EVs regularly, the power profile would be lower. Further, if not every EV has its own charging station, the power profiles would be lower for two reasons: (1) fewer EVs could provide FCR simultaneously as not all are connected and (2) more time of the charging station would be occupied for charging the energy for the mobility as several EVs have to be charged after a shift.

In our estimation we assumed that the pool operator does not plan an optimal charge management of each individual EV. Therefore, the estimated revenue is the potential for a fleet with an undisturbed charging profile. The active charging management of the EVs by the pool operator offers the possibility to increase the power available for FCR provision which in turn would increase the revenue. In [11] such a real-world operating strategy of FCR provision for a large-scale BSS is presented and discussed for the historic market design with the 30-min criterion. With an active charging management of each individual EV a pool operator could keep the fleet in a valid operating range to fulfill the 15-min criterion more often and to increase the pool's FCR power. Charge management often requires energy trading, e.g., from the continuous intraday market. One study [78] describing large-scale BSS operation in FCR market shows results where expenses for intraday recharge, trading services, and connection to trader sum up to about 15 % of income when operating 4 MW/4 MWh storage capacity.

Another way of charge management is the use of the “degrees of freedom” in the provision of FCR [79]. The ENTSO-E Handbook requests a minimum accuracy of the frequency measurement of 10 mHz. Therefore, FCR does not have to be provided if the deviation of the frequency is within 10 mHz from the nominal frequency of 50 Hz. However, FCR can be provided within this so called deadband. With the use of an accurate frequency measurement the charge management could opt to charge EVs with FCR in the deadband which reduces the costs of EV charging for users and can be regarded as additional revenue. Furthermore, due to power measurement accuracy limitations, an overfulfillment of provided FCR power of up to 20 % is permitted. Also, this degree of freedom could be used to maximize the energy gained for EVs during the provision of FCR and be seen as additional revenue. The last degree of freedom that can be taken advantage of by a pool operator is the specified ramp rate due to regulations. In the case of FCR, a total activation of the required power has to be activated within 30 s. A highly flexible unit, such as the battery of an EV, can react instantaneously in order to maximize energy when FCR is used to charge the EV. As an example for the impact of the degrees of freedom, one study [11] found that for a provision of 4 MW in the year 2014 with a large stationary storage system in Germany the energy gain due to the use of the degrees of freedom was 139 MWh. This rather complex topic for a real-world operating management for the provision of FCR with an EV fleet is a worthy research topic for the future.

5. Conclusion and outlook

This section draws a conclusion of the presented analyses and gives a brief outlook on market developments and future works.

5.1. Conclusion

Traditional grid services are undergoing a change of auction design towards flexibilization. A few years ago, the market for frequency containment reserve (FCR) to stabilize the grid frequency in Germany was provided exclusively by conventional power plants over service periods of up to one month. At present time, many large-scale battery storage systems as well as some battery pools are participating in the same market with service periods of less than one day. The market for FCR was a promising source of income for battery storage over the last years. After prices had fallen significantly in the face of the sharp increase in competition from battery storage systems, the prices increased sharply from 2021 onwards due to the political tensions with respect to gas imports and the war in Ukraine. This paper investigated the influence of FCR market flexibilization and FCR price development on the economics of EV fleet operation.

The service periods were shortened from one week over days to 4 h in accordance with the flexibility levels already achieved in the years until mid-2020. First, the average FCR price fell over years from 2585 €/MW/week during weekly service periods to an average price during daily service periods of 1281 €/MW/week. Then, the price increased to an average price of 2531 €/MW/week during the service period of 4 h.

Regarding the available power, the flexibilization from either one week to one day or the flexibilization from one day to 4 h cause the highest increase in mean available power. A power increase of up to 35 % resulting from the flexibilization of service periods from one week to one day can especially be seen for profiles that have regular driving profiles during the days Mon-Fri and little activity on the days Sat-Sun. However, for EV fleets that have the same driving pattern seven days a week, the further FCR flexibilization to service periods of 4 h is needed to significantly increase available power. This power can especially be provided during the idle times at night. Further, the times of high power show also only small values of power uncertainty. This makes commercial fleets especially interesting for V2G services as the idle times are known.

Future possible flexibilization in form of shorter service periods like one hour and less will only have a small impact on an increase in available power as the idle times are often already significantly longer than the current service period of 4 h. Therefore, future income will largely depend on the uncertain development of FCR prices.

While the potential revenue was on average below 250 €/EV/a during the daily service periods, the mean revenue increased to around 650 €/EV/a for the service periods of 4 h from mid-2020 to March 2022. However, in all analyzed scenarios, the revenues are relatively low, and it remains questionable if they can overcompensate for the costs for metering, battery degradation, and pool management.

5.2. Outlook

In the future, we expect the flexibility of the spot and ancillary service markets to increase further. In parallel with a rapidly increasing number of EVs, there will be a huge potential of mobile BSS in the energy system for the near future. From an economic point of view, it is advantageous to use EVs during their idle times for grid service instead of leaving this potential unused. With respect to these developments, it is questionable which flexibility markets will remain and in what form and whether there will be new markets. The analyzed FCR market, for instance, has a volume of below 600 MW. The regulatory agencies could decide to demand from EVs that they should have a frequency-dependent charging power profile. Such a law would effectively eliminate the FCR market as it is today. Such regulations are already part of the German renewable energy law (EEG), for example, which limits the feed-in power of photovoltaic systems. Furthermore, competition for aggregators will increase significantly. If there is enough battery capacity in the energy system, efficient pool management is essential.

CRediT authorship contribution statement

Jan Figgener: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. **Benedikt Tepe:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. **Fabian Rücker:** Conceptualization, Methodology, Data Curation, Writing - Review & Editing. **Ilka Schoeneberger:** Conceptualization, Methodology, Data Curation, Writing - Review & Editing. **Christopher Hecht:** Methodology, Writing - Review & Editing. **Andreas Jossen:** Resources, Writing - Review & Editing, Supervision. **Dirk Uwe Sauer:** Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A.1. Abbreviations and nomenclature

Table 5
Abbreviations sorted alphabetically.

AS	Ancillary services
BSS	Battery storage system
EEG	German renewable energy law
ENTSO-E	European Network of Transmission System Operators for Electricity
EPR	Energy-to-power ratio
EV	Electric vehicle
FCR	Frequency containment reserve
FNA	(German) Federal Network Agency
NACE	European Classification of Economic Activities
OCPP	Open Charge Point Protocol
PGS	Institute for Power Generation and Storage Systems
RWTH Aachen University	Rheinisch-Westfälische Technische Hochschule Aachen
SOC	State-of-charge
SOE	State-of-energy
TSO	Transmission System Operator
V2G	vehicle-to-grid
V2H	vehicle-to-home

Table 6
Nomenclature.

w_{start}	trip start probability
P_{EV}	Rated power of the battery converter
P_{CS}	Rated power of the charging station
P_{charge}	Charge power for FCR
$P_{discharge}$	Discharge power for FCR
E_{Bat}	Battery energy capacity
E_{market}	Marketable energy
$E_{mobility}$	Reserved energy for mobility
E_{charge}	Charge energy for FCR
$E_{discharge}$	Discharge energy for FCR
ΔT_{supply}	Duration of FCR service period

A.2. Additional information on used databases

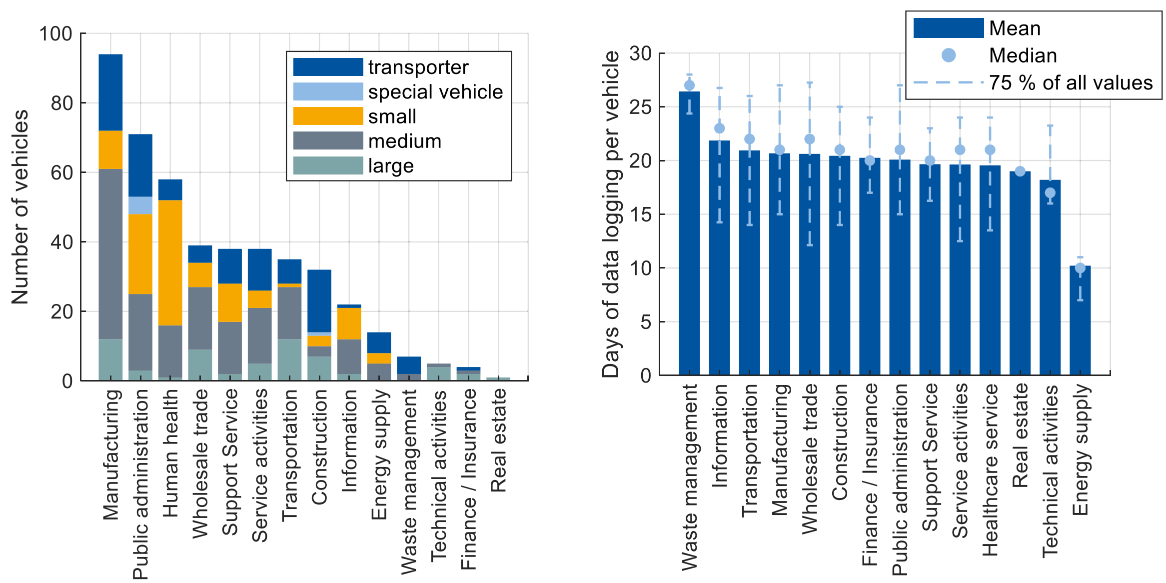

Fig. 23. Vehicles clustered according to economic sector (left) and mean duration of data logging (right) from database "Logbook".

Table 7
EVs from database "Measurements" used in the project GO-ELK [49]. Some EVs were switched between the different trades, which is why the number of EVs is greater than the measured 22 EVs.

Healthcare service	Energy supply	Transportation	Public administration
Smart E.D. (17,6 kWh)	Nissan e-NV200 (24 kWh)	Nissan Leaf (24 kWh)	Kangoo ZE (22 kWh)
Smart E.D. (17,6 kWh)	Nissan Leaf (24 kWh)	Opel Ampera (16,5 kWh)	Peugeot iOn (16 kWh)
Smart E.D. (17,6 kWh)	Nissan Leaf (24 kWh)	BMW i3 (21,6 kWh)	Peugeot iOn (16 kWh)
Mitsubishi i-MiEV (16 kWh)	Smart E.D. (17,6 kWh)	Smart E.D. (17,6 kWh)	
VW e-up! (18,7 kWh)	Kangoo ZE (22 kWh)	Smart E.D. (17,6 kWh)	
Opel Ampera (16,5 kWh)	Nissan Leaf (24 kWh)	Smart E.D. (17,6 kWh)	
Nissan Leaf (24 kWh)		Smart E.D. (17,6 kWh)	
		Nissan Leaf (24 kWh)	

Table 8
Electric vehicle data used to assume battery capacity and energy consumption for database "Logbook". Calculation based on data from ADAC [55].

Vehicle size	Differentiation in REM2030 according to cubic centimeters (cc)	Assumed differentiation *E*-vehicles	Brand & model	Battery Capacity kWh	Consumption kWh/100 km	ADAC Real Consumption kWh/100 km	Factor between nominal and real consumption	Vehicle weight kg	Torque Nm
Small	Displacement <1400 cc	Torque <220 Nm & Weight 1400 kg to 2000 kg	Citroën C-Zero	14.5	12.6	–	–	1440	196
			Citroën E-Mehari	30	20	–	–	1838	166
			Peugeot iOn	14.5	12.6	16.94	1.34	1450	180
			Renault Zoe (22 kWh) Life	22	13,3	21.4	1.61	1943	220
			Smart Fortwo coupé electric drive	17,6	15,1	19.2	1.27	1150	130
			Average	19.10	14.52	18.89	1.39	1545	179
			Assumed	19.1		18.9			
Medium	Displacement 1400 cc to 2000 cc	Torque 220 Nm to 380 Nm & Weight 1600 kg to 2200 kg	BMW i3 (94 Ah)	33.2	13.1	17.4	1.33	1620	250
			Ford Focus Electric	33.5	15.4	22.4	1.45	2085	250
			Hyundai Ioniq Elektro	28	11.5	14.7	1.28	1880	295
			KIA Soul EV	30	14.7	19.4	1.32	1960	285
			Mercedes-Benz B 250 e	28	16.6	20.2	1.22	2170	340
			Nissan Leaf	24	15	20.39	1.36	1965	280
			Opel Ampera-E	60	14.5	19.7	1.36	2056	360
			VW eGolf	24.2	12.7	18.2	1.43	1960	270
			Volvo C30 Electric	22.7	15	28.3	1.89	1995	220
			Average	31.36	14.35	20.08	1.40	1966	283
			Assumed	31.4		20.1			
Large	Displacement 1400 cc to 2000 cc	Torque 220 Nm to 380 Nm & Weight 1600 kg to 2200 kg	Audi e-tron 55 quattro	95	23	–	–	2565	664
			BMW Concept ix3 (2020)	70	17.5 (calc)	–	–		561
			Hyundai Kona Elektro	39.2	14.3	–	–	1760	395
			Jaguar I-Pace	90	21.2	27.6	1.32	2208	696
			Tesla Model S P90D	90	17.8	24	1.35	2670	967
			Tesla Model X	100	20.8	24	1.15	2534	660
			Average	80.7	19.31	24	1.27	–	680
			Assumed	80.7		27[a]			
Trans-porter	Displacement >1400 cc Weight < 3500 kg	Weight 1644 kg to 2600 kg & mostly 2–3 seats with a lot of storage size	Citroen Berlingo Electric L2	22.5	17.7 (NEFZ)	–	–	1644	200
			Iveco Daily Electric	28.2	–	–	–	2500	300
			Nissan e-NV200	24	16.5	22.8	1.38	1.640	254
			Peugeot Partner Electric	22.5	17.7	–	–	1664	152
			Renault Kangoo Z.E.	22	15.5	23.5	1.52	1520	226
			Streetscooter Work L Box	40	19.2 (NEFZ)	–	–	1640	200
			VW eCrafter	35.8	21.54	–	–	2522	290
			Average	27.86	18.02	23.15	1.45	2158	232
			Assumed	27.9		25.2[a]			

[a] As only few vehicles were tested by the ADAC, the real electricity consumption for large vehicles and transporter is calculated using the factor 1.4 (see small and medium average factor) and multiply it with the average nominal consumption.

A.3. Literature for further research

Table 9
Summary of **projects** working on the provision of ancillary services using EV fleets.

Source	Date	Name	Partner	Focus & results
[29]	2002	"Vehicle-to-Grid Demonstration Project: Grid Regulation Ancillary Service with a Battery Electric Vehicle" (V2GDP)	AC Propulsion, California Air Resources Board, California Environmental Protection Agency,	- Evaluation of the feasibility of the provision of grid regulation using EV - EV are able to provide grid regulation and the ISO system requirements regarding data transmission times could be fulfilled - Energy throughput when providing regulation power is equivalent to that resulting from daily driving
[31]	2012–2015	"Intelligente Netzanbindung von Elektrofahrzeugen zur Erbringung von Systemdienstleistungen – INEES"(Intelligent grid integration of EV to provide system services)	Fraunhofer IWES, LichtBlick SE, SMA Solar Technology AG, Volkswagen AG	- Field tests of the provision of secondary control reserve using a fleet of 20 V2G-capable EV - Provision is technically possible, but under current costs and revenue not profitable
[33]	2013–2018	Los Angeles Air Force Base Vehicle to Grid Demonstration (LAAFB)	Lawrence Berkeley National Laboratory (LBNL), Kisensum LLC	- Demonstration of a fleet of 29 bidirectional EV providing frequency regulation to generate revenue - Charging stations and EV should have a capacity/power ratio of at least two to participate in a fleet offering frequency regulation
[35]	2016–2019	The Parker Project (Parker)	DTU, Nuvve, Nissan, Insero, Enel X, Groupe PSA, Mitsubishi Corporation, Mitsubishi Motors Corporation, Frederiksberg Forsyning	- Demonstration project to analyze the integration of V2G-capable EV into the electricity grid - Results show that EV are able to provide ancillary services - Recommendations are the planning of electrification of transportation, continuous research, "test zones and pilots on new market designs" and an international collaboration
[42]	2018–2019	Industrial Pilot Project	The Mobility House, ENERVIE, Amprion, Nissan	- Demonstration of the provision of FCR using one EV that got prequalified from the German TSO
[43]	2019–2021	"Bidirectional Charging Management – Field Trial and Measurement Concept for Assessment of Novel Charging Strategies"	BMW, FfE e.V., FfE GmbH, Kostal Industrie Elektrik GmbH, TenneT TSO GmbH, Bayernwerk Netz GmbH, Karlsruhe Institute of Technology (KIT), University Passau	- Analysis of the interaction between EV, charging infrastructure and the power grid - Identification and demonstration (using 50 EV) of use-cases of V2G in different markets.
[45,46]	2019–2021	Industrial Pilot Project	Tennet, Next Kraftwerke, Jedlix	- Field test of EV providing frequency regulation in a virtual power plant - Customers of Jedlix charging their EV receive financial benefit when providing secondary control reserve

Table 10
Summary of literature about demonstrations, experiments and field tests of the provision of frequency regulation using EV fleets.

Source	Date	Project	Focus	Results
Brooks, Gage [30]	2001	V2GDP	Analysis of ancillary services EV, hybrid vehicles and fuel-cell vehicles may provide by showing test results	- Field tests show that the EV is capable of providing power and thus benefit to the grid - EV might be able to achieve lower net ownership costs in comparison to conventional vehicles by providing grid services
Marinelli et al. [36]	2016	Parker	Centralized approach to provide FCR with EV using unidirectional charging and experimental validation of the approach	- Provision of FCR with EV by only using unidirectional charging is viable with fast response time
Thingvad et al. [37]	2016	Parker	Economic comparison of EV fleet providing Frequency Normal-operation Reserve (FNR) through unidirectional vs. bidirectional (V2G) charging in Eastern Denmark	- Bidirectional FNR is more lucrative (factor of 6.6–13.3) and viable than unidirectional as it can be applied longer and independently of the driven distance - Experiments show that EV are able to perform unidirectional FNR and bidirectional FNR with delay times of 1 respectively 5 s
DeForest et al. [34]	2017	LAAFB	EV fleet participating in California Independent System Operator (CASIO) frequency regulation market	- Development of a Day-Ahead optimization model applied to the Los Angeles Air Force Base EV fleet minimizing operation cost and maximizing revenue from ancillary service
Degner et al. [32]	2017	INEES	Analysis of the effects of EV secondary control reserve provision on the distribution grid using simulations and field tests	- Power quality of the distribution grid is not negatively influenced by the EV provision - The EV impact on the distribution grid can be anticipated and managed well
Hashemi et al. [38]	2018	Parker	Presentation of results from three different EV (Nissan Leaf, Peugeot iOn and Mitsubishi Outlander) providing FCR-N (frequency-controlled normal operation reserve) in Nord Pool energy market	- All three EV were able to response within five seconds and with an accuracy of around 98 % - The depth-of-discharges (DoDs) were always smaller than 40 %

(continued on next page)

Table 10 (*continued*)

Source	Date	Project	Focus	Results
Bañol Arias et al. [39]	2018	Parker	Analysis of an EV fleet participating in Danish FNR market and determination of issues appearing in the field	- EV fleet is able to support the grid, e.g. in FNR market, but availability of the EV is crucial - Practical issues are "communication delays, measurement errors and physical equipment constraints" [39]
Thingvad et al. [40]	2019	Parker	Economic analysis of EV performing FNR in the Nordic countries considering requirements and losses	- The value of bidirectional FNR is much higher than providing unidirectional FNR - Suggestion: Aggregator should pay for the EV's driving energy consumption to remunerate owners - Losses due to charger's efficiency results in reduced revenue by 22 %
Bañol Arias et al. [41]	2020	Parker	Economic assessment of EV participating in FCR-N in the Nord Pool market from the owner's perspective applying three operation strategies: complete pause, over-fulfillment, preferred operating point	- EV owners can achieve profits from the provision of FCR—N, mostly when choosing a smart operation strategy - Preferred operating point strategy resulted in highest profits (up to 1100€ per EV per year when bidding 10 kW) as it minimized the battery degradation and the unavailability times

Table 11
Summary of selected literature of German rules and regulations on the frequency containment reserve (FCR) market.

Source	Date	Content related to the provision of FCR using battery energy storage systems
VDN [80]	2007	TransmissionCode 2007: Network and system rules of the German transmission system operators In Appendix D: Documents for prequalification for the Provision of primary control power to TSO - Degrees of freedom, rules and requirements that must be met by a provider of FCR
FNA [65]	2011	German federal network agency (FNA) changes FCR bidding time from monthly to weekly
German TSO [79]	2014	Key points and degrees of freedom for the provision of FCR using BSS as an example
German TSO [70]	2015	Storage capacity requirements for the provision of FCR using batteries (e.g. 30-min-criterion)
FNA [64]	2018	German federal network agency (FNA) changes FCR bidding time from weekly to daily starting in July 2019 and from daily to 6 daily sections of 4 h starting in July 2020.
FNA [12]	2019	Decision of the German federal network agency (FNA) to stop the TSO from requiring the 30-min-criterion when providing FCR with BSS. From now on 15-min-criterion for all providers including BSS.
German TSOs [72]	2019	Minimal requirements on the IT when providing control reserve. When pooling small systems (< 25 kW per system, maximum pool size 2 MW) the connection between the systems can from now on be made via the internet.

Fig. 24. Mean annual revenue (left) and revenue change (right) of the economic sectors.

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