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Balancing group deviation & balancing energy costs due to the provision of frequency containment reserve with a battery storage system in Germany

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ABSTRACT

The energy transition in the electrical energy supply sector is leading to a steadily increasing share of fluctuating renewable energy sources in the power grid. Thus, control reserves such as frequency containment reserve are gaining in importance and need further investigation. In Germany, the power grid is divided into balancing groups, in which supply and demand must be balanced out. The provision of frequency containment reserve, creates an imbalance in the respective balancing group depending on the grid condition. However, this energetic imbalance and the resulting costs for the balancing group manager are further to be quantified. This work provides a simulation model that examines the energetic imbalances resulting from the provision of frequency containment reserve. We validate the simulation results with field-data from the operation of a 6 MW battery storage system and derive the resulting cost for the energy imbalances. In addition, flexibility options for batteries given by the regulatory framework in form of the degrees of freedom are evaluated. The results show, that the degrees of freedom enable a battery storage operator to additionally charge up to 8.68 MWh/MW frequency containment reserve per month or dis-charge up to 9 MWh/MW frequency containment reserve per month on average. The additional profits from the German imbalance settlement price vary on average between 302 € and 1,068 € per MW frequency containment reserve per month. In Conclusion, the field-data confirm the simulation data in terms of energy deviations in the balancing group due to the provision of FCR. Over the period of one month, the deviation usually leads to a cost-related advantage for the balancing group manager. The provision of frequency containment reserve as a grid service can therefore be seen as a positive gain for a balancing group.

1. Introduction

In the following section, frequency containment reserve, imbalance settlement pricing and the interrelationships in the German market are described. In addition, the deviation of the balancing groups by frequency containment reserve is highlighted. The analysis is focused on battery storage systems for providing frequency containment reserve. Thereafter, a literature review is presented.

1.1. Frequency containment reserve and grid imbalance settlement pricing

In Germany, there are three different types of control reserves to keep the power grid stable. Frequency containment reserve (FCR) is the fastest type of control reserve [1,2]. The provision of FCR is a grid service that is tendered and awarded in Germany by the transmission system operators (TSOs) across all control areas [2,3]. Particularly in view of the increasing share of volatile renewable energies, a stable transmission grid and thus reserve capacities will be necessary in the future [4].

The provision of FCR is regulated and defined with a characteristic power curve (see Fig. 1) [1,5]. For the providers of FCR, so-called degrees of freedom (DOF) are defined for operation. Fig. 1 shows the characteristic power curve as a function of the frequency for FCR in Germany [5,6]. For frequencies lower than 50 Hz, the FCR provider has to supply power to the grid. For frequencies above 50 Hz, the FCR

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Nomenclature

BG	Balancing group (Bilanzkreis)
BGM	Balancing group manager (Bilanzkreisverantwortlicher)
DOF	Degree of freedom (Freiheitsgrad)
FCR	Frequency containment reserve (Primärregelleistung)'
ISP	German Imbalance Settlement Price (regelzonenübergreifender Bilanzkreisausgleichspreis, reBAP)
M5BAT	Modularer Multi-Megawatt Multi-Technologie Mittelspannungs-Batteriespeicher (Eng.: modular multi megawatt multi-technology medium voltage battery storage system)
TSO	Transmission system operator (Übertragungsnetzbetreiber)
SOC	State of Charge

provider has to take power from the grid. The deadband in Fig. 1 is a range of 50 Hz ±10 mHz in which no action is required from the FCR provider [7]. As an additional DOF, the FCR provider can optionally provide FCR in this range according to the characteristic curve. For FCR providers, an overfulfillment up to 20 % more than the standard curve is possible [7]. This DOF is shown in Fig. 1 as the purple curve.

The FCR service can be provided by battery storage systems. Since battery storage systems are highly efficient and have short response times, battery storage systems are well suited for FCR or faster grid services. Related to battery storage supplying power to the grid means discharging while taking power from the grid means charging the battery storage. Battery storage operators can use the DOF to maintain their state of charge (SOC) in a range around 50% in order to be able to charge or discharge [7].

In Germany among other countries, the TSOs have the task to keep the grid stable [8]. In the reserve power market the FCR power is tendered and allocated in 4-hour blocks one day before delivery [1,9]. As shown in Fig. 2, the TSO is responsible for the auction and pays the FCR suppliers for their service. The FCR providers have to deliver the service in accordance to the current grid status in this case the grid frequency.

Besides the reserve market, the TSOs have the instrument of balancing energy [1]. Balancing energy describes the actual energy flow compared to the contractual energy flow between the different balancing groups (BG) and is allocated in 15-minute blocks [10]. The balancing energy can only be determined ex post, i.e. after the past 15 min. Therefore, it is a description of the deviation of the actual energy flow from the forecast of the BGMs. As presented in Fig. 2, the flow of the balancing energy is the indicator whether a BG is oversupplied, undersupplied or balanced. For the deviation from the BGMs forecast, a payment between BGM and TSO is necessary. The payment is based on the German imbalance settlement price (ISP). The ISP itself is calculated by the TSO and dependent on the grid status and the respective costs for the TSO in the reserve market [11,12].

1.2. Deviation of a balance group by FCR

Since FCR as a grid service is dependent on the measured grid frequency (cf. Fig. 1) and therefore cannot be planned, FCR causes a deviation or imbalance of the balancing group because the mean frequency over 15 min is not always equal to 50 Hz. By using the degrees of freedom (DOF, see Section 1.1) in providing FCR, the deviation effects can be more or less pronounced. For a battery storage system as a unit providing FCR, the DOF can be used for recharging or discharging as one form of energy or SOC management. The SOC management also called setpoint adjustment describes charging or discharging a battery storage to maintain a certain SOC-level and to match certain power prognosis. This is needed to fulfill the prequalification criteria for the provision of FCR in the German market. In the prequalification conditions stated by the grid code, the use of the degrees of freedom as a means to manage the storage's SOC is explicitly proposed [7]. It is important to note that the DOF cannot be the only option for energy or SOC management. Since the occurrence of DOF cannot be planned, another strategy such as intraday trading as a form of setpoint adjustment is necessary for storage management. There also are further requirements in the prequalification conditions for the use of DOF [7].

As described by Thien et al. the setpoint adjustment as a form of energy or SOC management is a trigger to buy or sell energy on the intraday market for the upcoming 15 min. By recharging or discharging through the intraday market the setpoint in form of a power prognosis or the SOC is adjusted to a level that matches the criterion from the grid code [5,14].

This paper also shows which costs or profits are generated by the ISP through the deviation of the BG and through the use of the DOF while

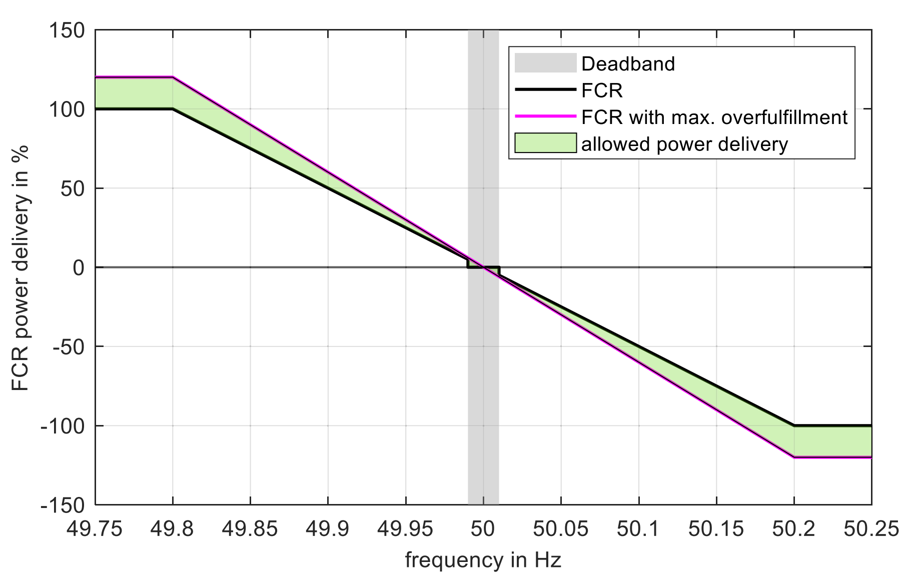

Fig. 1. Characteristic curve for the power provision of FCR in Germany. [5, 7].

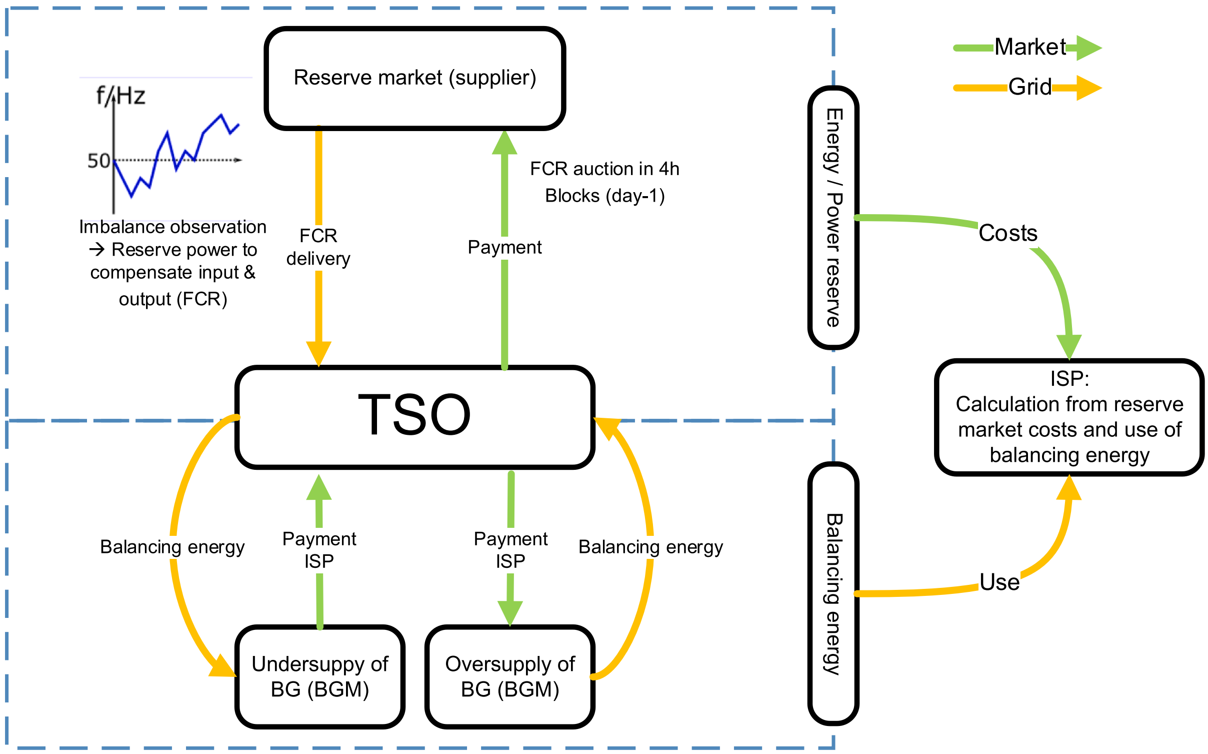

Fig. 2. Connections between the balancing energy and the reserve power and resulting payments [13].

providing FCR. This is important because the costs or profits are covered by the BGM, while setpoint adjustments via intraday trading are covered by the FCR unit operator. The conflict of interest of the costs between BGM and FCR unit operator is to be resolved in this work.

1.3. Literature review

Different aspects of the German electricity market have already been studied. Table 1 shows a number of sources and their insights into the FCR market and the imbalance market, as well as the connections between the market and renewable energy generation. As the market is continuously evolving, the reactions of the market participants and their strategies are also changing [3,15,16]. The FCR market and regulatory framework spans over several European countries where the same or similar grid services and incentives for reducing imbalances exist [17,18]. The most recent conditions and regulations for FCR can be found at [7]. Furthermore, there is a further development and expansion of the power grid to meet the challenges of the energy transition and create the capacity for more renewable energies [19]. The influence of renewable energies on the spot market was also investigated by Goodarzi et al. and Ocker and Ehrhart. They found that a high amount of volatile energy production increases the forecast error and causes higher imbalances [4]. This does not automatically mean that more reserve power is required [2]. The changing market mechanisms and the strategic behavior of market participants in the German market were also studied [20]. Schäfer et al. investigated grid frequency fluctuations, but did not draw a connection to the reserve market or the FCR service [21]. From the market and the observed grid, studies on operating strategies of FCR plants result [5,22]. Especially the use of DOFs for battery storages were identified as important element for the provision of FCR [5,22]. The imbalance market and balancing energies have also been studied [23–26]. However, a distinct investigation of the relationship between FCR output and the imbalance market has not yet been conducted. In this paper, the direct impact of the provision of FCR on the imbalance market cost is examined from the perspective of the BGM. The behavior of battery-powered FCR plants is clearly shown. Moreover, field data measurements are shown and compared to the performed simulations.

1.4. Data

The data used for this study is provided by the TSO TransnetBW and is available online [30, 31]. The period from 01.07.2018 to 30.06.2021 is used. The data for validation (section 5.5) corresponds to the same period and originates from the battery storage M5Bat.

2. General study of the imbalance settlement price and the grid frequency

The product FCR, is tendered and awarded via different countries in Europe such as Germany, Netherlands, Belgium, Denmark, Austria, Switzerland, Slovenia and France. The prices for this are known after the daily auction. However, the quantities of energy provided by FCR are unknown, since it is a grid service based on the currently measured grid frequency.

The ISP is uniform throughout Germany and is calculated by the grid operators ex post operation. The prices are shown in €/MWh and are calculated on the basis of the control energy cost that incurred and the corresponding control energy quantities per quarter hour [10]. Depending on the supply of the balancing group (oversupply or undersupply) and the direction of a transaction, payments are due from the BGM to the TSO or vice versa from the TSO to the BGM.

Fig. 2 shows the interconnections between the reserve market, FCR delivery and the calculation and payment of the ISP. In the following, the relation between the ISP and the grid frequency are examined in general.

2.1. General information on ISP

The boxplots in Fig. 3 show the distribution of the ISP prices for each half year in the investigated period. Outliers are neglected to increase readability. The distribution reveals that most prices are positive. This

Table 1
Literature on balancing energy and the reserve market in Europe and Germany.

Source	Related topic	Key message	Region (time)
Chaves-Ávila et al. [24]	Mechanism for imbalance pricing and network utilization	Issues in the current imbalance pricing model and possible alternative designs for imbalance pricing.	Germany (2013)
Goodarzi et al. [4]	Impact of renewable energy on network imbalance and electricity prices	Larger volatile energy production increase the forecast error and cause higher levels of imbalance and subsequent the market prices.	Europe (2019)
Koch [25]	Strategic Intraday Bidding to use imbalance pricing	Demonstration that it is possible to create profitable trading strategies based on expected imbalance pricing.	Germany (2019)
Ocker and Ehrhart [2]	Development of the balancing market and energy production	Development of the German market shows that despite higher renewable energy production shares no additional reserve power is required.	Germany (2015)
Badedaa et al. [27]	Battery storage systems in the reserve market	Development of a FCR market model. Influence factors on the market development and battery storages are shown.	Germany (2017)
Schlachter et al. [6]	Use of battery storage systems for FCR	Optimal system configuration for a battery storage in combination with a Power-to-Heat module to deliver FCR.	Germany (2020)
Schweer et al. [22]	Provision of FCR from battery storage (example M5BAT)	The capacity limits battery storages in providing FCR. Usage of DOFs can generate additional benefits.	Germany (2016)
Hollinger et al. [28]	Use of DOF in battery systems providing Fast frequency response	Envelopes of enhanced frequency response (Great Britain) have a large potential for SOC management in battery storages.	Great Britain (2018)
Hollinger et al. [29]	Use of DOF in battery systems providing FCR	The DOFs should be implemented and used for SOC management in battery storages.	Germany (2016)
Mbavarira and Imboden [18]	European Grid Service Markets overview	Overview over grid services and price levels for grid services in European countries	Europe (2020)
Fleer and Stenzel [17]	European Grid Service and operating strategy for battery systems	Regulatory framework for FCR in Europe and Operating strategy for FCR providing units	Europe (2016)
Münderlein et al. [14] Schweer et al. [22] Thien et al. [5]	Battery Storage M5BAT	Operation strategies, and setpoint adjustments for providing frequency containment reserve at the battery storage M5BAT	Germany (2016–2020)

indicates that for an oversupplied BG the BGM gets paid from the TSO while for an undersupplied BG the BGM has to pay the TSO. The plots show a slight U-curve for the mean ISP prices, with the lowest mean values in the first half-year of 2020. In 2021, the scattering of the ISP prices increases compared to older values. The mean ISP price is around 42 €/MWh for the whole period, while the mean positive ISP price is roughly 49 €/MWh and the mean negative ISP price is around −7 €/MWh. Because of various changes in the market the maximum ISP price limit has changed in the past and new components were added to the calculation [11,12,32].

To find out if the ISP has a periodical (weekly) dependency, Fig. 4 depicts the weekly median. No significant characteristics are revealed, except that the mean prices are always positive and on weekends lower than on weekdays. The average for a weekday is 45.6 € while the average for the weekend is 32.9 €. Also, prices on weekends are more often negative than on weekdays.

2.2. Frequency and FCR mean week

The diagram in Fig. 5 shows the recorded frequency as boxplots for each half year. The lines under and above the whiskers of the boxplots are the outliers in this time range. The average value over the 3-year period is 50 Hz, which corresponds exactly to the nominal frequency. The highest share of frequencies are in the range of 50 Hz +/- 10 mHz, which is the defined deadband. The deadband limits are marked with the red horizontal lines in Fig. 5. It is also clear that frequency deviations to lower frequencies are more pronounced than deviations to higher frequencies. The lowest frequency values are around 49.75 Hz, while the highest are just above 50.15 Hz.

Fig. 6 shows the superposition of all days in the period under investigation in the form of a median value graph. Additionally, areas for 50 % and 75 % of the frequency values are shown.

It is clearly visible that the strongest frequency deviations occur in the minute around the full hour. At full hours in the morning, there are deviations to higher frequencies, while in the afternoon and evening there are frequency deviations to lower frequencies below 50 Hz. This pattern is evident from Monday to Friday. On the weekend, however, the average deviations are much less pronounced. The pattern suggests that power plants are, based on trading intervals on the spot market, turned on at the top of the hour in the morning, while power plants are turned off at the top of the hour in the evening. For the provision of FCR, this means that the largest power request can be expected at the top of the hour. The variations of the frequency are less strong on weekends especially on Sundays.

3. Methodology

This section presents the used assumptions for the simulation as well as the four different simulation cases. Furthermore, the definitions for the energy flow and the cash flow are pointed out.

3.1. Simulation model and assumptions for quantification

In order to determine the costs or profits resulting from the provision of FCR in the form of balancing energy, a theoretical analysis is carried out that is afterwards compared to measured operation data (see Section 4). For this purpose, a simple model of FCR including DOF for use of the deadband and overfulfillment is created with the following assumptions and restrictions:

- There is no time lag in the frequency deviation and the provision of FCR.
  - o (cf. real connection conditions and conditions of FCR).
- The perfect FCR characteristic curves are executed, there are no control deviations.
- Only the FCR-providing plant exists in the virtual balancing group.
  - o The balancing group is otherwise perfectly balanced
- The balancing energy costs are calculated exactly per kWh.
- All calculations refer to 15 min and 1 MW of FCR
- Possible gaps in the published time series are not considered in detail [31]
- The storage providing FCR is infinitely large, so no setpoint adjustment is needed

Like mentioned in Section 1.4 the frequency and ISP data originate from the TSO TransnetBW and can be found online [30,31].

In addition to the standard case without DOF, three DOF cases were identified and calculated that could have the most relevant impact on the balancing group. Thus, the calculated results represent extrema for energy and resulting costs or profits. The analyzed cases are listed in

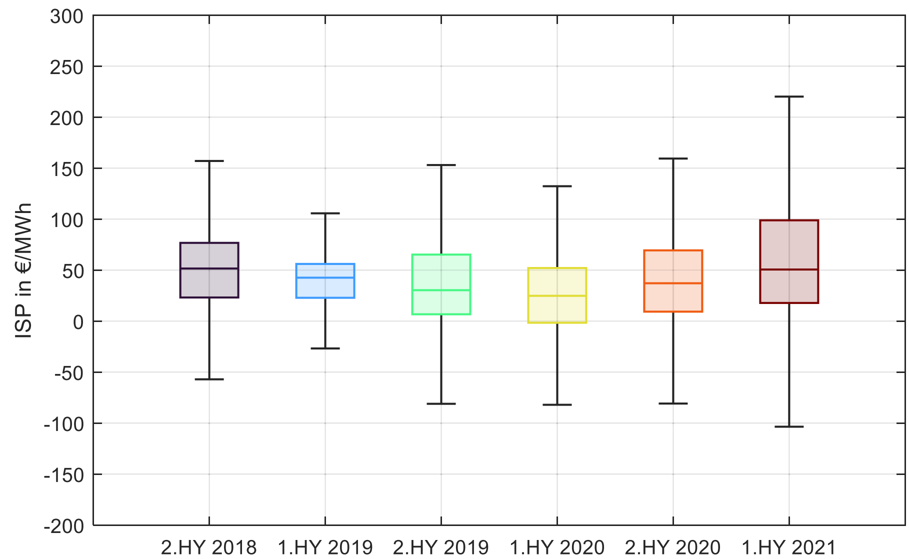

Fig. 3. Boxplots for each half year for the ISP prices. Outliers are not shown [30].

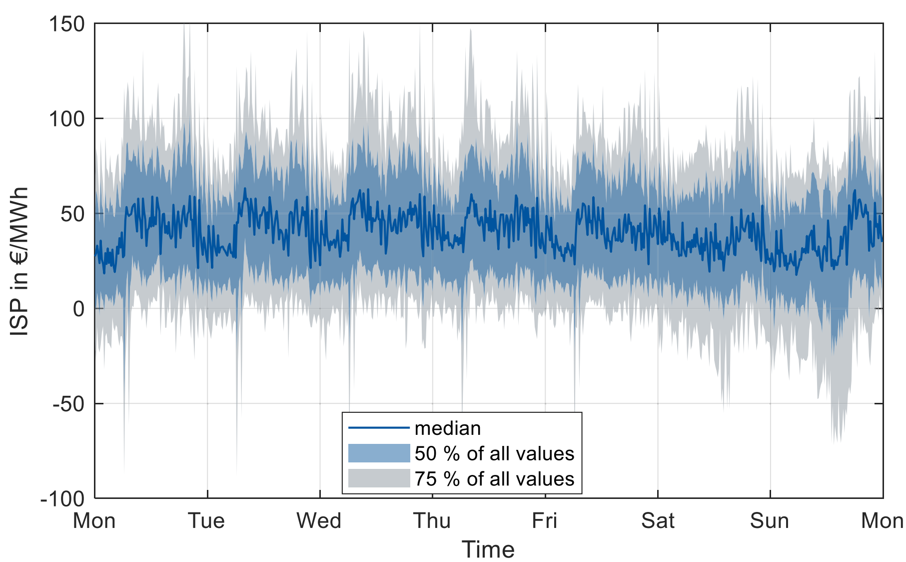

Fig. 4. ISP prices over the time period 07/2018 until 06/2021 shown as median and share of all values over a week [30].

Table 2. The special cases only charge and only discharge can be important for battery storage systems or combined systems with renewable energy production. Battery storage operators use the only charge DOF case to minimize cost and energy to balance out the current SOC and save on recharging. For a combined production of solar power and batteries the only discharging DOF can be interesting to avoid reducing the feed in power.

For a battery storage system using the only charge DOF results in a higher average SOC than the non-use of the DOFs. Also, the only charge DOF reduce the intraday recharging trades and lowers expenses for the battery storage operator. Nevertheless, the use of DOFs causes higher energy throughput and thus higher loads on the batteries which increases battery aging.

3.2. Definitions for energy and profit

In order to be able to evaluate the simulation results, the definitions from Table 3 are introduced. The energy balance E is calculated by Equation (1). Therefore the power P resulting from FCR delivery is used in time steps t of 1 s. Values for the energy balance E are only calculated for each 15 min because the energy deviation is only considered every 15 min.

$$E = \sum_{t_0=0}^{t_1=15min} P(t)^{*} t \tag{1}$$

For the calculation of the profit the energy values for 15 min are necessary. The profit is defined as a positive payment from the TSO towards the BGM. A negative profit is stated as a loss for the BGM. For the calculation, the 15 min energy balance values are multiplied with the ISP price for the same 15 min window. The value for the time window T in Equation (2) is always given and used in a 15 min time interval. The times T_0 and T_1 in Equation (2) represent the time horizon that is investigated. For this work the time horizon is a monthly time step.

$$\text{Profit} = \sum_{T_0}^{T_1} E(T) \cdot \text{ISP}(T) \tag{2}$$

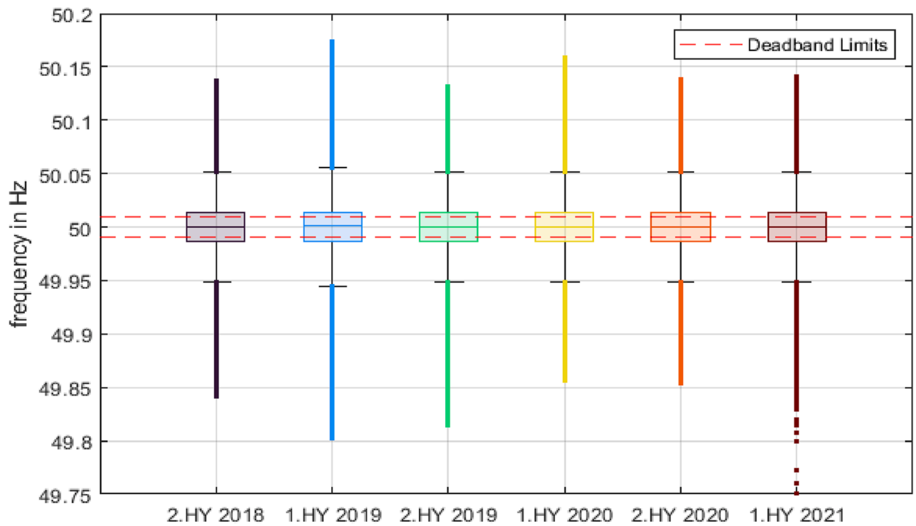

Fig. 5. Distribution of the frequency time series. Data from [31].

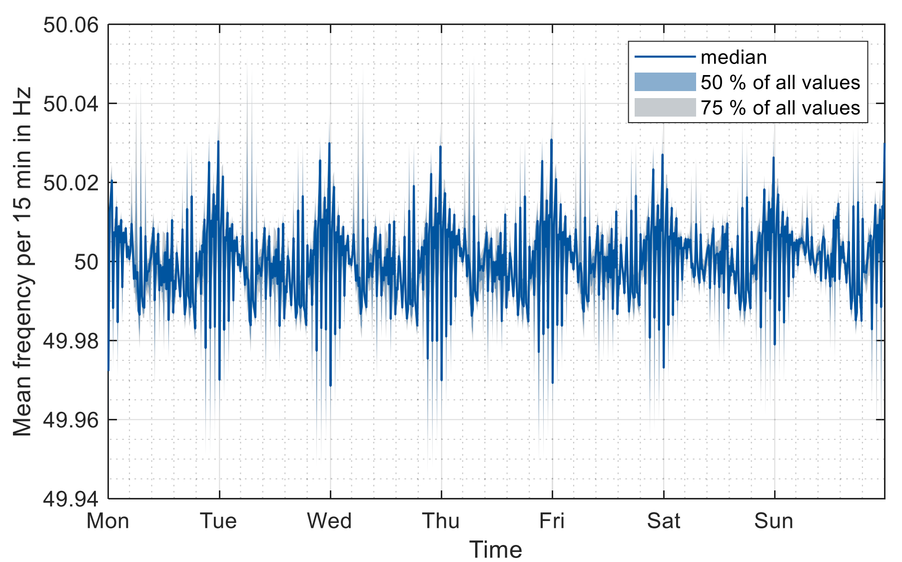

Fig. 6. median week of the grid frequency for the time from 07/2018 till 06/2021 [31].

Table 2
Investigated cases.

FCR Case	Description
Without DOF	Calculation of the FCR without use of any DOF
DOF both	Calculation of the FCR with use of DOF in charging and discharging direction for overfulfillment and use of the deadband.
DOF only charge	Calculation of the FCR with use of DOF in charging direction for overfulfillment and use of the deadband
DOF only discharge	Calculation of the FCR with use of DOF in discharging direction for overfulfillment and use of the deadband

Table 3
Definitions for energy and payment directions from the point of view of the BGM.

Values	description	Further description
$E > 0$	Oversupplied BG	More discharging through FCR from storage was performed
$E < 0$	Undersupplied BG	More charging through FCR from storage was performed
$E = 0$	“Ideal grid”	No deviation over 15 min period
Profit > 0	Payment from TSO to BGM	Payment direction from the point of view of the BGM
Profit < 0	Payment from BGM to TSO	

4. Results and discussion

In this section, the results from the simulations are presented and a comparison to measured field data is made. The data compared are the second-by-second power values, the aggregated 15 min energy amounts, and the resulting costs due to energetic imbalances. The correlations between ISP and FCR and the resulting energy quantities and costs or profits are highlighted.

4.1. Correlation between frequency and ISP

With the analysis of the correlation between the mean frequency over 15 min and the ISP a structural advantage or disadvantage of delivering FCR on the balance sheet deviation can be demonstrated. Table 4 shows the correlation between the mean frequency over 15 min and the ISP. A distinction is made between the entire dataset and partial datasets.

For the entire dataset, the correlation is −0.01, which is a small correlation. A negative correlation means that low or negative ISP costs are expected for higher average frequency values, while higher ISPs are expected for lower average frequency values. Since the outliers of the ISP can have a greater impact on the cash flows, the correlations are examined separately. According to Table 4, the correlation increases with larger outliers. For outliers > 1,000 €/MWh there is a moderate correlation of −0.25. For the payment flows between the BGM and the TSO this means that there is a structural correlation in favor of the FCR provider or the BGM in which the FCR-providing unit is located. At high ISP and thus low frequencies < 50 Hz, the FCR unit would contribute to the oversupply of the BG and thus cause a payment flow in favor of the BGM (see also Fig. 2). At high frequencies > 50 Hz the FCR unit would contribute to the undersupply of the BG (see also Fig. 2). In this case, a negative ISP causes a cash flow from the TSO to the BGM. For battery storage systems as FCR units contributing to the BGs oversupply means discharging the battery.

Fig. 7 shows the previously described relationship visually that high frequency deviations towards lower mean frequencies lead to higher ISP prices and higher mean frequencies lead to lower or negative ISP prices. The diagram also reveals that negative ISP prices occur less often than the positive ones.

4.2. FCR energy throughput and deviation

The energy throughput is the sum of the energy fed in or taken out from the grid. In case of a battery storage system the energy throughput is the charged or discharged energy for a specific time horizon. Fig. 8 shows the average energy throughput per 15 min for the charging and discharging directions in the four cases (see Section 3.1) described above. Fig. 9 shows the energy deviation or balancing group deviation per 15 min per MW of marketed FCR.

Fig. 8 shows that the use of the DOF increases the energy throughput by an average of approx. 3 kWh/(15 min*MW) or 1.2% of the reserved FCR capacity. The lowest energy throughput for the charging and discharging directions therefore occurs when the degrees of freedom are not used. The values are about 9 kWh/(15 min * MW) or 3.6 % of the reserved FCR capacity. Using the degrees of freedom would thus result in an average energy or setpoint adjustment of up to 3 kWh/(15 min * MW) 1.2 % of the reserved FCR capacity. It is also visible from the graph that, based on the frequency, slightly more energy is required for discharging than for charging during the period under investigation (for the cases without degrees of freedom and with degrees of freedom in both directions).

Since the frequency distribution and thus the required FCR is not needed equally in every quarter hour, a distribution can be revealed when considering the entire period. In the following, only the distribution of the energy deviation, i.e. the difference between the required charging and discharging energy, is considered. The energy deviation indicates whether balancing energy costs could accrue. Fig. 9 shows this distribution.

The distribution in Fig. 9 on the left side shows the energy balance caused by FCR without using the DOFs in the virtual BG in kWh/MW. The red cross marks the mean value in this distribution, while each dot is an energy aggregation over 15 min. For the without DOF case there are many quarter hours with minimal or no energetic balance. But some quarter hours have large energetic imbalances. Higher energy values result in payments between TSO and BGM. On the right side in Fig. 9, the distributions show the difference from the distribution on the left side. The difference for each quarter hour is always calculated as the difference between the case without DOF minus the DOF case (DOF both, DOF only Charge or DOF only Discharge). It is visible that the energy deviation for the use of DOFs in both directions are larger. The unsymmetrical use of the DOFs creates a shift towards negative values for the charging case and a shift towards positive values for the discharging case.

Table 4
Correlation between the mean frequency f for 15 min and the ISP.

Dataset	Pearson correlation coefficient
Complete dataset	−0.012
Only outlier > abs(250 €/MWh)	−0.098
Only outlier > abs(500 €/MWh)	−0.225
Only outlier > abs(1,000 €/MWh)	−0.251

4.3. Energy and cash flows on a monthly basis

In the following, for the four cases under investigation, the energy quantities and resulting cash flows are examined on a monthly basis. Losses of the BESS are not determined nor shown. During operation, however, losses occur depending on the technology and components of the BESS, making it necessary to adjust the setpoint.

As shown in Fig. 10, the amount of energy deviation from FCR at no DOF and DOF in both directions varies around 0 MWh/MW FCR. There are variations of up to 5 MWh on a monthly basis. For the case only charging DOF, there is a shift to the negative range. The average is −8.68 MWh/MW FCR per month, which means that this energy can be charged for the cost of balance group deviation. The only charging DOF thus enables a recharging quantity of just under 9 MWh/MW FCR per month when fully utilized.

For the case only discharging DOF, there is a corresponding shift to positive values to an average of 9.01 MWh/MW FCR per month. Thus, this energy may be delivered to the grid per month.

For the profits and losses from the BGM's point of view, a trend towards increasing profits can be seen in Fig. 11 for all cases under investigation. Since the monthly energy throughput of FCR-providing units did not increase during the observed period and ISP prices did not increase steadily, the increased profits result from a favorable time dependence of ISP and FCR power delivery. This confirms that the ISP is used as an incentive system and grid-serving behavior is rewarded, while the rewards are increasing over time. For the entire period, the arrangement shows that *only discharge DOF* produces the largest profits, followed by *DOF in both directions* and *no DOF*. The case *only charge DOF* yields the lowest profits (until mid 2019 partly also losses).

If just the *only charge DOF* is used, the profits through ISP prices are lower on the BGM's side, but from the FCR unit operator's point of view less or no recharges are necessary for setpoint adjustment. For the FCR unit operator, fewer recharges or even a sale of energy on the power exchange are significantly more advantageous.

4.4. Energy and cash flows for the investigated period

For the entire period under investigation (1st July 2018 until 30th June 2021), the energy quantities and profits for the BGM are shown in Table 5. The picture remains the same as before on a monthly basis. The profits for the BGM are highest when the only discharge DOF is utilized, followed by DOF in both directions and non-utilization of the DOF. DOF only in the charging direction results in the lowest profits, which are however close to 10,900 €/MW FCR for the whole investigated period of 3 years. On a monthly basis this would be a mean profit of around 302 €/MW FCR.

The deviations in terms of energy show a higher discharge of 10.79 MWh/MW from FCR when the degrees of freedom are not used. With full use of the DOF, there is a reduction of the deviation to 4.49 MWh/MW. For one-sided use of the DOF, there are significantly larger energy deviations. For both directions, the deviations are above 300 MWh/MW FCR.

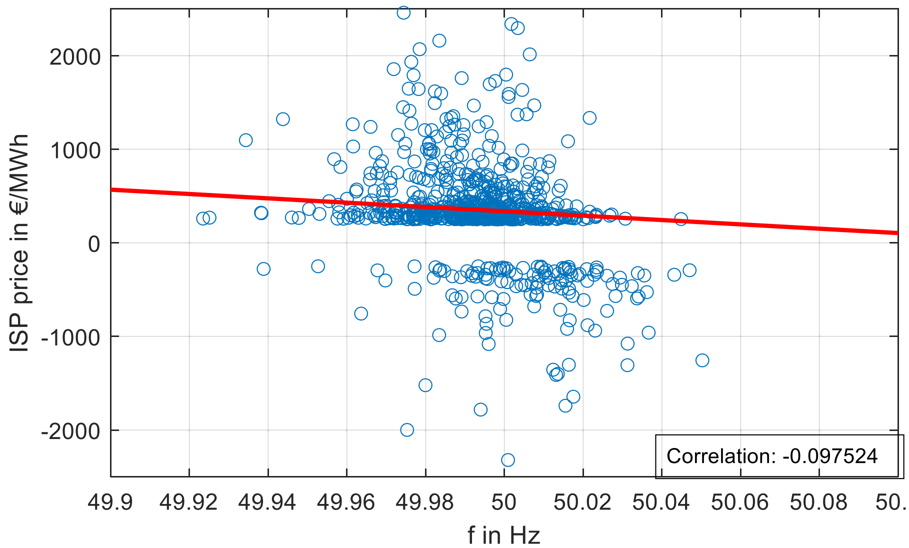

Fig. 7. Correlation between the 15 min mean frequency and the ISP for outliers with an absolute value > 250 €/MWh.

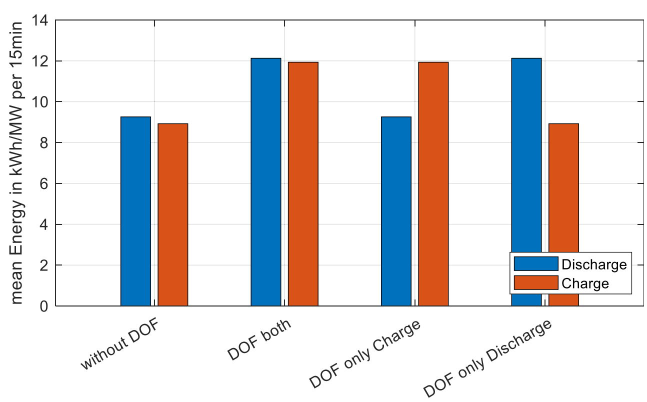

Fig. 8. Mean energy throughput per 15 min in charging and discharging direction for provision of FCR (Note: for a 30-day period the discharging energy throughput is exemplarily 26.6 MWh, which corresponds to nearly one equivalent full cycle per day).

4.5. Comparison to real world data

Since the simulation as described in Section 3.1 involves some boundary conditions and assumptions, there is a comparison between the simulation results and the field-data collected by the operation of the M5BAT battery storage in the following. M5BAT is the acronym for modular multi megawatt multi-technology medium voltage battery storage system. This stationary battery storage system is located in Aachen, Germany and contains batteries with a maximum power of around 6 MW and an energy storage capacity of around 7.5 MWh. Since 2016, the battery storage M5BAT is in operation for research purposes and delivers FCR in the German market. Currently, M5BAT is prequalified to deliver up to 3 MW of FCR. Due to research projects and issues with some batteries, the prequalified 3 MW are not always tendered. All field-data from M5BAT are normalized to 1 MW of FCR to make a useful comparison with the simulation data.

The degrees of freedom have not been used for the battery storage M5BAT since 23rd September 2020. Therefore, the period from 23rd September 2020 to 30th June 2021, is used as the comparison period for the non-use of the DOF. For the use of the DOF, the period from

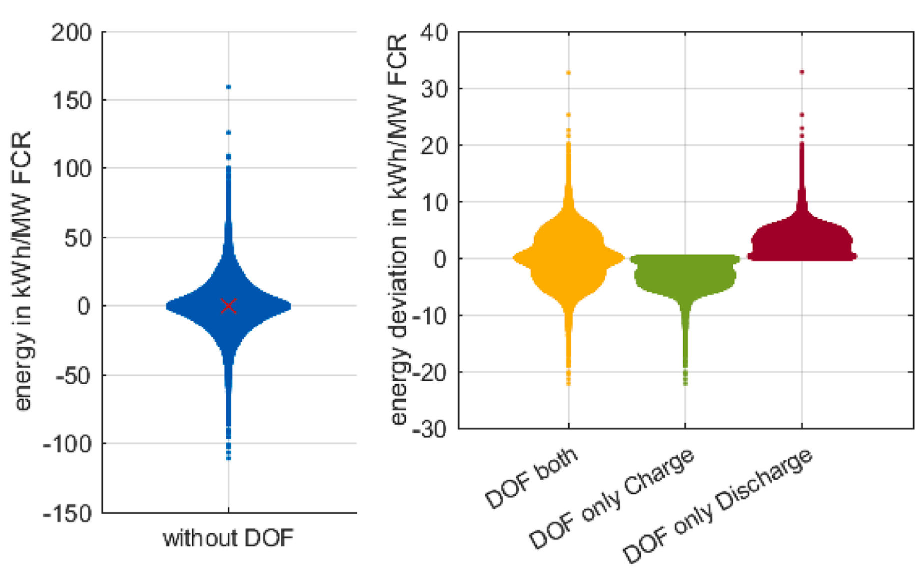

Fig. 9. Energy balance and energy deviation for the four investigated cases according to Table 2. Left: Energy balance caused only by FCR without using DOF in BG in kWh/MW for 15 min; Right: Difference from FCR without DOF in kWh/MW for 15 min energy value.

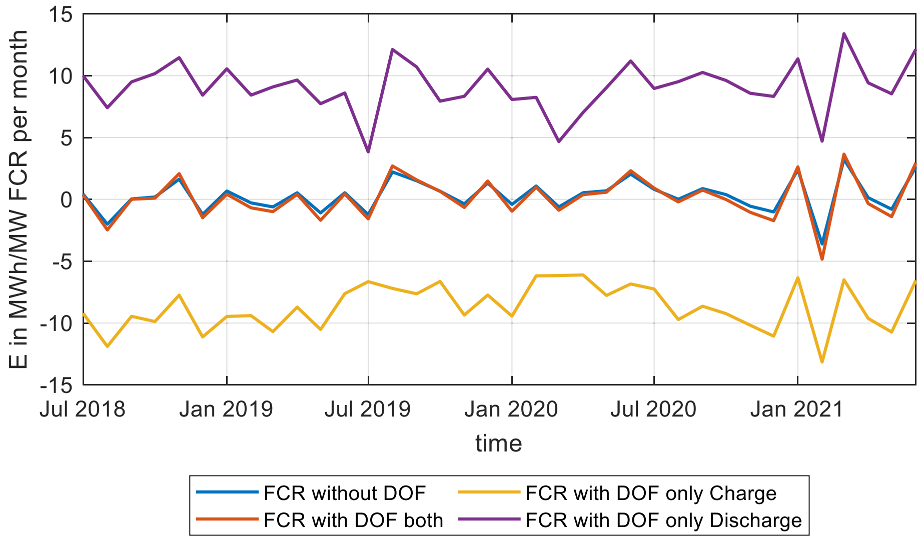

Fig. 10. Energy deviation by providing FCR in different settings on a monthly basis form the BGM's point of view.

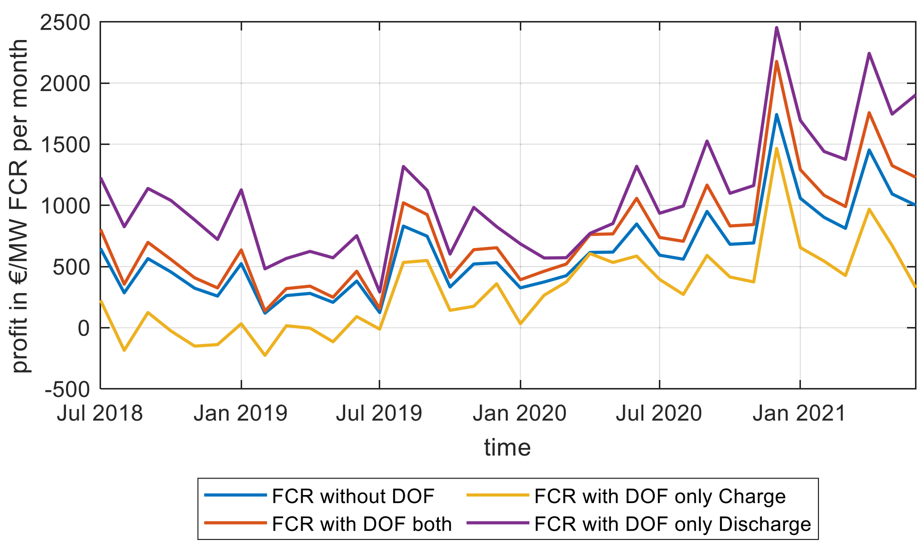

Fig. 11. Profit (Cash flows) in balancing energy costs by providing FCR in different settings on a monthly basis.

Table 5
energy deviation and profits by ISP for different FCR options for the investigated period (07/2018 until 06/2021).

FCR option	Without DOF	With DOF	DOF only charge	DOF only Discharge
Energy deviation in MWh/MW FCR	10.79	4.49	−312.31	327.59
Profit by ISP in €/MW FCR	22,147	27,198	10,896	38,449

01.07.2018 to 23.09.2020 is used. Since DOFs are used in the M5BAT battery storage system depending on the SOC, it is first necessary to clarify which simulation offers the best possible comparison. The SOC-dependent utilization of DOFs has been developed over several years of operational experience and is composed as follows: If the SOC was<70%, the charging DOFs were used. Above 80% SOC only the discharge DOF were used and in the range between 70 and 80% SOC, no degrees of freedom were used [5]. Since certain amounts of energy and power must be held in reserve for the provision of FCR, depending on the FCR offered, the battery storage can only be used in medium SOC ranges. The efficiency of the M5BAT battery storage of approximately 73% means that more energy has to be charged than can be discharged. This results in an asymmetry, which can be compensated by SPA or by a one-sided use of the DOFs. Since the average state of charge in operation is about 50% SOC, only the DOF in the charging direction is usually used when the DOFs are activated. Therefore, we use the only charging DOF as a comparison case from the simulations.

Fig. 12 shows the comparison of energy deviations per 15 min. The data and trends produced by the simulations can be confirmed with the field-data. There are minor deviations, but the overall distribution is very similar. These differences to the field-data exist, because the measurements in M5BAT are not perfect and a PI-controller must correct the losses from transformers and inverters, which causes slight variations in the output power of M5BAT. This explains especially the energy deviations around 0 kWh/(MW*15 min). Even for the comparison for the use of the DOFs the histograms overlap each other for the largest part.

In addition to the deviations in the energy quantities, the ISP results in profits or losses each 15 min. In Fig. 13, negative profits are correspondingly losses. The time periods are the same as previously described for Fig. 12. The graph only shows the range from −5 to 5 €/MW per 15

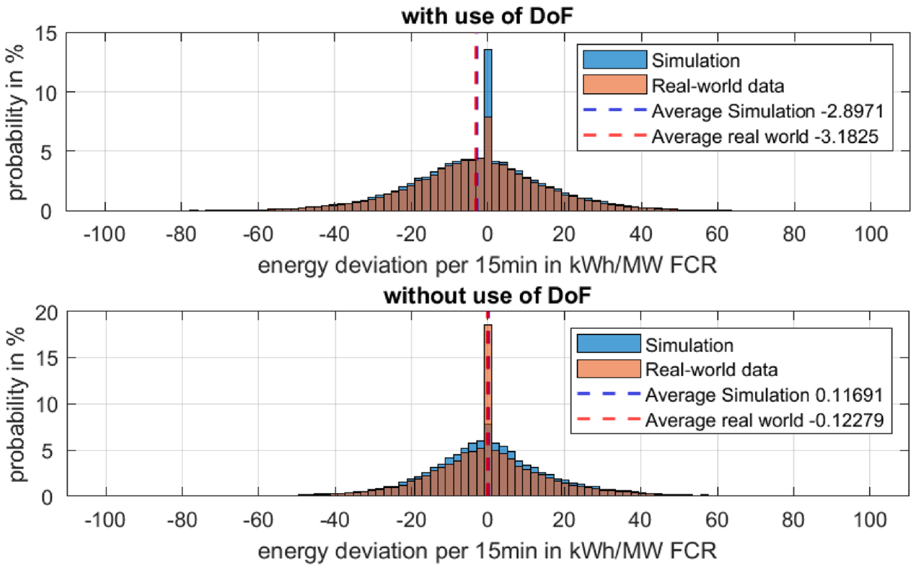

Fig. 12. Comparison between field-data and simulation data for the energy deviation per 15 min; outliers above 100 kWh/MW FCR or below −100 kWh/MW are not shown. Upper graph: comparison for the use of DOF (01.07.2018 until 23.09.2020). Lower graph: comparison for the data without use of DOF (23.09.2020 until 30.06.2021).

min. All outliers are thus cut off. This results in a slight shift of the mean values away from the center of the histogram. The mean values show that independent of the considered case a profit per 15 min can always be expected due to the energy deviation. Again, the field-data confirm the trend of the simulations even if the profits for the field-data are slightly lower than the profits calculated from the simulations. The field-data support the findings that the profits are higher for not using the DOFs than the only charge DOF case as discovered in Section 4.4. According to the shape of the histogram a large portion of the profits for not using the DOFs comes from outliers. This can be observed by the shift of the mean values away from the center of the histogram.

5. Conclusion and outlook

In summary, the markets for reserve power and balancing power are linked by the quantities of supplied energy and the market prices. For the provision of FCR, this coupling means an economical advantage, since the grid-serving behavior is additionally rewarded by the provision of FCR via the ISP.

Based on the simulations, energy throughputs of 26.6 MWh/MW for the discharging direction and 25.7 MWh/MW for the charging direction without considering DOF are obtained for one month. When DOF is used, these values increase to 34.9 MWh/MW for the discharging direction and 34.3 MWh/MW for the charging direction. The difference in energy between use and non-use of the DOF offers operators of battery storage systems the possibility of adjusting the operating point. Since for battery storage the losses can be compensated by the DOF from charging, the simulation for the use of the DOF from charging shows that the profit from the ISP is reduced by this. The profits for the most profitable case only Discharge DOF can be quantified as 1068 €/MW FCR per month. For a battery storage operator the only charge DOF case is the most interesting case because the setpoint adjustments can be reduced to a minimum. The monthly profits for this case are quantified at 302 €/MW FCR. In this case the battery storage operator uses the only

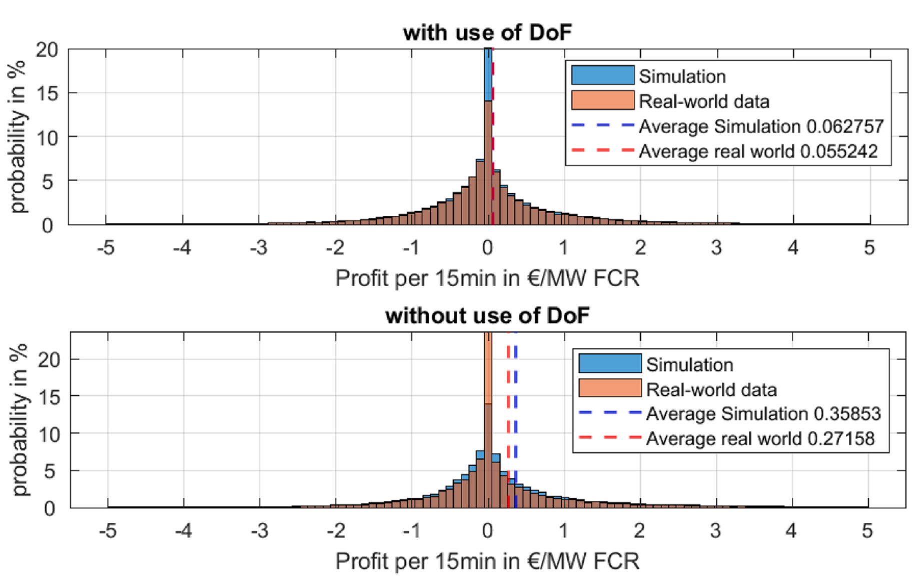

Fig. 13. Comparison between field-data and simulation data for the profit per 15 min; outliers above 5 €/MW FCR or below −5 €/MW are not shown: Upper graph: comparison for the use of DOF (01.07.2018 until 23.09.2020); Lower graph: comparison for the data without use of DOF (23.09.2020 until 30.06.2021).

charge DOF to recharge and keep the battery storage system in a medium SOC according to the FCR conditions. In contrast to direct recharging via the spot market, no direct payment from the battery storage operator is necessary.

The comparison of the simulations with the field-data from the battery storage M5BAT confirms the simulations and the associated profits from the ISP of a battery storage opera-tor for the BGM. The shown histograms overlap in largest parts.

As a further investigation, the gains from the BG deviation can be compared to the costs of the charge energy or the avoided costs from not charging. Thus, an even more comprehensive cost advantage or disadvantage can be quantified. Here, the intraday prices for the reload energy as well as the level of the ISP and the current network situation are decisive. Another investigation approach could be the difference between a centralized system like M5BAT and a decentralized system with many small FCR providing units, which are controlled like a Pool-solution for FCR.

CRediT authorship contribution statement

Lucas Koltermann: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Kevin Jacqué:** Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing – review & editing. **Jan Figgener:** Conceptualization, Validation, Writing – review & editing, Supervision. **Sebastian Zurmühlen:** Validation, Writing – review & editing, Project administration, Funding acquisition. **Dirk Uwe Sauer:** Validation, Resources, Writing – review & editing, Supervision, Funding acquisition.

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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