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Abstract:

In order to increase self-consumption (SC) more than half of the residential photovoltaic (PV) systems in Germany are installed with battery storage systems (BSS). The utilization of these BSSs however varies throughout the year and therefore they could be used for other services to further increase their profitability. Recent changes in regulation for frequency containment reserve (FCR) facilitate multi-use concepts and first aggregators are already prequalified for the German market. Against this background, we analyze the potential for the joint provision of FCR and SC increase from residential BSSs with a linear optimization model applied to 162 German households. Different scenarios including fixed shares of the BSS reserved for FCR, priorization of SC or a joint optimization of SC and FCR are examined. We find that fixed shares of FCR only lead to minimal additional financial benefits. Both, the joint optimization of FCR and SC and prioritizing SC lead to higher additional gains, while the loss in SC is low in both scenarios. Moreover, even when prioritizing SC still high shares of the BSS can be used for FCR. Only a significant increase in FCR prices leads to SC being sacrificed for higher FCR shares.

Keywords: Frequency containment reserve; Residential battery storage system; Self-consumption; Multi-use; Pooling

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Nomenclature

Abbreviations

FCR	frequency containment reserve
FIT	feed-in tariff
PV	photovoltaic
SC	self consumption
SOC	state of charge

Parameters

Δt	time step length (SC) [h]
Δt^{FCR}	time step length (FCR) [h]
$\eta_{\mathrm{ac}\rightarrow\mathrm{bat}}$	charging efficiency [–]
$\eta_{\mathrm{bat}\rightarrow\mathrm{ac}}$	discharging efficiency [–]
η_{bat}	battery efficiency [–]
$\tau_{\mathrm{min}}^{\mathrm{FCR}}$	minimum reserved time for FCR activation [h]
$\varepsilon_{\mathrm{neg}}^{\mathrm{FCR}}$	share of neg. FCR activation time [–]
$\varepsilon_{\mathrm{pos}}^{\mathrm{FCR}}$	share of pos. FCR activation time [–]
c^{el}	cost of electricity from grid [EUR/kWh]
$c^{\mathrm{FCR}}, \tilde{c}^{\mathrm{FCR}}$	remuneration for FCR provision [EUR/kW]
c^{FIT}	remuneration for electricity fed into the grid [EUR/kWh]
$E_{\mathrm{bat}}^{\mathrm{loss}}$	battery self discharge per time step (SC) [kWh]
$E_{\mathrm{bat}}^{\mathrm{max}}$	battery storage volume [kWh]
$P_{\mathrm{bat}}^{\mathrm{max}}$	battery (dis)charging power [kW]

Sets and Indices

t	time step (SC) [–]
t^{FCR}	time step (FCR) [–]

Variables

$\lambda^{\mathrm{FCR}}, \tilde{\lambda}^{\mathrm{FCR}}$	share of battery power used for FCR [–]
$E_{\mathrm{bat}}^{\mathrm{SC}}$	artificial battery SOC [kWh]
$E_{\mathrm{bat}}^{\mathrm{total}}$	battery SOC [kWh]
$P_{\mathrm{bat,in}}^{\mathrm{FCR}}$	battery charging (neg. FCR) [kW]
$P_{\mathrm{bat,out}}^{\mathrm{FCR}}$	battery discharging (pos. FCR) [kW]
$P_{\mathrm{curt}}^{\mathrm{FCR}}$	PV curtailment (neg. FCR) [kW]
$P_{\mathrm{grid,in}}^{\mathrm{FCR}}$	feed-in to grid (FCR) [kW]
$P_{\mathrm{bat,in}}^{\mathrm{SC}}$	battery charging (SC) [kW]
$P_{\mathrm{bat,out}}^{\mathrm{SC}}$	battery discharging (SC) [kW]
$P_{\mathrm{curt}}^{\mathrm{SC}}$	PV curtailment (SC) [kW]
$P_{\mathrm{grid,in}}^{\mathrm{SC}}$	feed-in to grid (SC) [kW]
$P_{\mathrm{grid,out}}^{\mathrm{SC}}$	withdrawal from grid (SC) [kW]
$P_{\mathrm{hh,in}}^{\mathrm{SC}}$	direct SC of household [kW]
$P_{\mathrm{hh,out}}$	electricity demand of household [kW]
P_{pv}	PV generation [kW]

1 Introduction

In recent years the feed-in tariffs (FIT) for rooftop photovoltaic (PV) systems in Germany have declined considerably. As a consequence, PV systems are only profitable if part of the electricity can be self-consumed (Ritter et al., 2021). Due to cost reductions of battery storage systems (BSS) and increasing retail electricity prices, about half of the residential PV systems in Germany are installed with BSSs to further increase self-consumption (SC) (Bundesverband Solarwirtschaft, 2021). By the end of 2021, roughly 400 thousand BSSs with over 3.5 GWh were already installed (Figgener et al., 2022a), thus Germany accounts for 70 % of the the European market for residential BSSs (SolarPower Europe, 2021).

These BSSs are however only slightly used for SC increase during winter months and could therefore be used for other services to potentially increase their profitability (Angenendt et al., 2020). Especially frequency containment reserve (FCR) could be suitable as an additional service. FCR is one of the highest value services and BSSs are well suited for it due to their their fast ramp up rate (Engels et al., 2019). The share of utility-scale BSSs in the German FCR market was already about two thirds in 2019 (Figgener et al., 2022b). FCR is a service where power capacity is offered. Savings from SC, on the other hand, are mainly driven by energy capacity, therefore potential synergies arise (Engels et al., 2019). Some aggregators of residential BSSs were already prequalified for the German FCR market, namely Caterva (later: Alelion Energy Systems GmbH), Ampard AG (Lichtblick) and sonnen eServices GmbH (Angenendt, 2021). Caterva and its successor however filed for bankruptcy (Enkhardt, 2019). Recently the regulation for the FCR market was updated (see Section 2) increasing the attractiveness for multi-use concepts (Figgener et al., 2022b).

Although some studies have already analyzed the joint provision of FCR and SC from residential BSSs, our work complements the existing literature in several important aspects. Typically, seasonal fluctuations in the utilization of the BSS for SC are not considered. Furthermore, the share of the BSS used for FCR is not dynamically optimized thus underestimating potential economic benefits from additional FCR provision. As the newly introduced regulation strongly increases flexibility, this is especially important. Moreover, most of the existing studies only analyze a few load profiles and system configurations. In contrast, we apply an optimization model to 162 households with varying system configurations to determine the optimal share of the BSS used to provide FCR over the course of a full year. An analysis with such a level of detail is unique in the literature to date and allows us to derive robust results for various different framework conditions.

The remainder of this paper is structured as follows. Section 2 outlines recent changes in regulation for the FCR market. In Section 3 we present an overview of existing literature regarding the FCR provision from residential BSSs and deduce the research gap that our paper intends to fill. Section 4 then introduces the modeling in detail. Based on this, we analyze the results in Section 5 and provide a sensitivity analysis. In Section 6 we discuss the limitations of our study. We summarize our findings and draw conclusions in Section 7.

2 Regulation

In the following, we provide some background on frequency regulation in Germany.

Frequency regulation is divided into FCR, automatic frequency restoration reserve (aFRR) and manual frequency restoration reserve (mFRR)(ENTSO-E, 2020). FCR has to be provided automatically within 30 seconds, if a frequency deviation of more than 10 mHz occurs.

Germany is part of the Continental Europe Synchronous Area, which has a total required reserve capacity for FCR of 3000 MW (ENTSO-E, 2020). The share for each control area is based on its share in the overall electricity generation and consumption of the synchronous area and updated yearly (Consentec, 2022). Over the past years, the German FCR demand ranged from 551 MW to 620 MW (BNetzA, 2021).

A service provider has to be prequalified to proof that it is able to meet the technical requirements for providing FCR (Consentec, 2022). These include the ability to provide the desired power in positive and negative direction within 30 seconds and for at least 15 minutes. Until 2019, BSSs had to be able to provide FCR for at least 30 minutes, but this was ruled to be discriminating BSS operators by the German federal network agency (BNetzA) (BNetzA, 2019). Additionally, a buffer of 25 % of the prequalified power has to be maintained (German Transmission Grid Operators: 50 Hertz, Amprion, Tennet, TransnetBW, 2022b). As previously mentioned, some aggregators of residential BSSs were already prequalified for the German FCR market (Angenendt, 2021).

Various changes to the design of the FCR tenders were made in the past years, which are briefly summarized in the following.

First, service periods for FCR were adjusted several times. Until 2011, FCR had to be provided for one month continuously (Figgener et al., 2022b). In 2011, the service period was reduced to one week (BNetzA, 2011). Another reduction to 24 hours occurred in July 2019 (BNetzA, 2018), but only lasted for a year. Finally, in July 2020, the flexibility was increased further by introducing six daily FCR service slots of four hours each (BNetzA, 2018).

Second, in line with shorter service periods, also the lead times were reduced a few times (Figgener et al., 2022b). Between 2011 and 2019, the FCR tender was held weekly, always on Tuesday at 3 pm. With the introduction of daily service periods, the lead time was changed to two days. Currently, the auctions are held every day for the next day.

Third, in 2011, the minimum bid size was reduced from 5 MW to 1 MW (BNetzA, 2011).

Fourth, the remuneration scheme was changed in 2019 from a pay-as-bid auction to uniform pricing (BNetzA, 2018).

Combined, these changes have increased the flexibility of the FCR market and increased the attractiveness for multi-use concepts (Figgener et al., 2022b).

3 Literature Review and Research Gap

The provision of FCR with BSSs has been investigated and shown to be possibly profitable in different studies (Stephan et al., 2016; Fleer et al., 2018). Also the combination of different applications has been studied (e.g., Braeuer et al., 2019; Maeyaert et al., 2020) – a good overview in this regard is provided by Figgener et al. (2022b). However, given the scope of our work, the following literature review explicitly focuses on the combination of SC and FCR.

Braam et al. (2016) simulate a single family household in Germany that simultaneously engages in SC and provides FCR. The household has an annual electricity consumption of 4600 kWh, a 7 kW_p PV system and a 10 kWh/10 kW BSS. A constant 6 kW of FCR are offered throughout the year, which is later varied in a sensitivity analysis. The authors conclude that even though there is a considerable decrease in SC, the earnings from FCR might still make the combination of applications profitable.

Steber (2017) simulate a complete Virtual Power Plant providing 1 MW of FCR. It replicates the business model of Caterva. Synthetic load profiles are used for 65 households, which all are equipped with a 5.75 kW_p PV system and a 21 kWh/20 kW BSS. As the BSS is quite large compared to systems normally installed for SC increase, the households reach high SC and self-sufficiency rates, despite offering an average of 15.4 kW of FCR. According to the calculations, the installation of the battery is still profitable for the households due to the earnings from FCR provision.

Maeyaert et al. (2020) present a model for the operation of residential BSSs while stacking services. For the combination of FCR with SC increase, 44 households in Belgium represented by synthetic load profiles are analyzed. All households are equipped with a 4 kW_p PV system and either a 7 kWh BSS offering a constant 2.4 kW of FCR or a 14 kWh BSS offering a constant 4.5 kW of FCR. Also in this work, the authors conclude that the combination of services increases the economic potential of the BSS.

Gomez-Gonzalez et al. (2020) present a model for jointly optimizing the sizing and power management of two Spanish prosumer households. PV and BSSs as well as electric vehicles are considered for increasing SC and providing FCR. The model has a yearly horizon and a constant 2.5 kW of FCR are offered. Given the model assumptions, an investment in BSSs is profitable and even more so, when the joint application of the BSS for SC increase and FCR provision is considered.

Stephan et al. (2016) develop a techno-economic model to analyze the combination of various different applications. Their dispatch algorithm has an hourly resolution and the applications are split in an hierarchical order into primary and secondary applications. SC is considered a primary application and FCR is only provided when the BSS is idle. A single household in Germany with a 5 kW_p PV system is analyzed, and the size of the BSS is determined endogenously. Even though FCR increases profitability, an investment in a BSS is not profitable under the assumptions made in this paper.

Angenendt et al. (2020) investigate the provision of FCR with a BSS and power-to-heat coupling. A German household with a 10 kW_p PV system, 10 kWh/10 kW battery and 10 kW_{th} heat pump is analyzed. Additionally to different levels of constant FCR provision, a scenario with a weekly variation of the FCR provision is presented. In this scenario, the FCR share is increased stepwise, until the energy-throughput in the given week is reduced by 20 %. An average of 5.9 kW of FCR are offered, with higher shares being offered in winter. The authors conclude that a seasonal variation of the FCR share can increase profitability.

Engels et al. (2019) propose a model that maximizes the value generated by the BSS by increasing SC and providing FCR. The share of FCR is optimized endogenously. The model is applied to one weekday in March and a German household equipped with 4 kW_p of PV, and a 10 kWh/7 kW BSS. Synthetic household load profiles are generated with the the CREST model (Richardson et al., 2010). The authors find that earnings can be increased by about one fourth as compared to single applications.

Englberger et al. (2020) publish an optimization framework for stacking of multiple applications including SC increase, FCR provision, peak shaving and spot market trading. It is applied to a commercial consumer in Germany operating a utility-scale BSS. SC is analyzed in this paper, but not considered viable, because the residual load of the commercial consumer is rarely negative and therefore the possibilities for additional energy savings are very limited. To the best of our knowledge, this is the only study, which already incorporates the new German regulation for FCR and therefore varies the optimal FCR share on a 4-hourly basis. However, at the time of this work, market data was only available for the first half of 2019. The authors conclude that besides increasing the profits, application stacking can also reduce risks like a significantly reduced remuneration for FCR provision.

In summary, although a number of relevant studies already exist, our work complements the existing literature by a number of important aspects. As previously described, most of the related literature does not consider seasonal fluctuations in the utilization of the BSS for SC. Moreover, most of the existing studies do not dynamically optimize the share of the BSS used for FCR provision, thereby underestimating the economic benefits from the additional FCR provisioning. This is especially important, as the newly introduced regulation strongly increases flexibility (see Section 2). Furthermore, only few load profiles and system configurations are typically analyzed in the literature. In contrast, our paper considers 162 individual households for each of which the optimal share of the BSS used for FCR provision is determined dynamically over the course of a full year. An analysis with this level of detail is so far unique in the literature and allows us to derive robust results for a variety of different framework conditions.

4 Methodology and Data

As previously mentioned the focus of this paper is on the operation of the BSS in a way, that jointly maximizes the savings from SC and the additional revenues from FCR. The model developed for this analysis is presented in Section 4.1, and the data used as well as the main assumptions in Section 4.2.

4.1 Optimization model

We develop a linear optimization model that takes the perspective of an individual prosumage household and minimizes its net cost of electricity consumption defined as the cost of electricity drawn from the grid minus revenues from the grid feed-in of surplus PV electricity and providing FCR:

$$\min \sum_t \Bigg(\underbrace{P^{\mathrm{SC}}_{\mathrm{grid,out}}(t) \cdot \Delta t \cdot c^{\mathrm{el}}}_{\text{cost of electricity from grid}} - \underbrace{P^{\mathrm{SC}}_{\mathrm{grid,in}}(t) \cdot \Delta t \cdot c^{\mathrm{FIT}}}_{\text{feed-in remuneration}} - \underbrace{\lambda^{\mathrm{FCR}}(t) \cdot P^{\mathrm{max}}_{\mathrm{bat}} \cdot c^{\mathrm{FCR}}(t)}_{\text{revenues from FCR provision}} \Bigg). \tag{1}$$

This cost minimization is carried out subject to a number of constraints. First and foremost, the electricity demand of the household needs to be covered by SC of PV generation, battery discharging and withdrawal of electricity from the grid:

$$P_{\mathrm{hh,out}}(t) = P^{\mathrm{SC}}_{\mathrm{hh,in}}(t) + P^{\mathrm{SC}}_{\mathrm{bat,out}}(t) + P^{\mathrm{SC}}_{\mathrm{grid,out}}(t) \quad \forall t. \tag{2}$$

At the same time, all electricity generated from the household's PV system needs to be used for (a) direct SC, (b) battery charging, (c) grid feed-in at the applicable FIT, (d) curtailment of excess generation, (e) grid feed-in to provide positive FCR, and (f) additional curtailment to provide negative FCR. This energy balance of the PV system is formulated as follows:

$$P_{\mathrm{pv}}(t) = P^{\mathrm{SC}}_{\mathrm{hh,in}}(t) + P^{\mathrm{SC}}_{\mathrm{bat,in}}(t) + P^{\mathrm{SC}}_{\mathrm{grid,in}}(t) + P^{\mathrm{SC}}_{\mathrm{curt}}(t) + P^{\mathrm{FCR}}_{\mathrm{grid,in}}(t) + P^{\mathrm{FCR}}_{\mathrm{curt}}(t) \quad \forall t. \tag{3}$$

Moreover, the battery's state of charge (SOC) needs to be monitored in order to ensure that the storage never runs full or empty. The SOC for each time step can be determined by the SOC of the previous time step plus battery charging (to increase SC or provide negative FCR) and minus battery discharging (to increase SC or provide positive FCR) as well as losses through self discharge:

$$E_{\text{bat}}^{\text{total}}(t) = E_{\text{bat}}^{\text{total}}(t-1) + \left(P_{\text{bat,in}}^{\text{SC}}(t) + P_{\text{bat,in}}^{\text{FCR}}(t)\right) \cdot \Delta t \cdot \eta_{\text{ac}\rightarrow\text{bat}} \cdot \eta_{\text{bat}} - \left(P_{\text{bat,out}}^{\text{SC}}(t) + P_{\text{bat,out}}^{\text{FCR}}(t)\right) \cdot \frac{\Delta t}{\eta_{\text{bat}\rightarrow\text{ac}}} - E_{\text{bat}}^{\text{loss}} \quad \forall t. \quad (4)$$

Thereby, the initial SOC and the final SOC are set equal to ensure a proper energy balance over the whole optimization period:

$$E_{\text{bat}}^{\text{total}}(0) = E_{\text{bat}}^{\text{total}}(t_{\text{max}}). \quad (5)$$

In case the respective household provides FCR, a certain fraction of both, the storage power and energy volume needs to be reserved, and is not available to increase SC. Thus, a second artificial SOC needs to be monitored[1], which only considers the battery operation to increase SC. The constraints are formulated analogously to those previously described, however with different lower and upper bounds for the SOC (as detailed below):

$$E_{\text{bat}}^{\text{SC}}(t) = E_{\text{bat}}^{\text{SC}}(t-1) + P_{\text{bat,in}}^{\text{SC}}(t) \cdot \Delta t \cdot \eta_{\text{ac}\rightarrow\text{bat}} \cdot \eta_{\text{bat}} - P_{\text{bat,out}}^{\text{SC}}(t) \cdot \frac{\Delta t}{\eta_{\text{bat}\rightarrow\text{ac}}} - E_{\text{bat}}^{\text{loss}} \quad \forall t, \quad (6)$$

$$E_{\text{bat}}^{\text{SC}}(0) = E_{\text{bat}}^{\text{SC}}(t_{\text{max}}). \quad (7)$$

Since we do not only model the theoretical provision of FCR, but also the actual activations, another energy balance for FCR needs to be set up. For each time step, we compute the share of positive and negative activation time. This allows us to determine a net FCR activation for the whole time step, which can be either negative or positive. The activation then needs to be fulfilled by the

[1]Please note that following the current German regulation, the electricity used for battery charging to provide negative FCR may not be used for SC afterwards. This is implicitly guaranteed in our model by monitoring two different SOCs.

household through grid feed-in and battery discharging (positive FCR), or battery charging and curtailment of PV generation (negative FCR):

$$\left(\varepsilon_{\text{pos}}^{\text{FCR}}(t)-\varepsilon_{\text{neg}}^{\text{FCR}}(t)\right)\cdot\lambda^{\text{FCR}}(t)\cdot P_{\text{bat}}^{\max} = P_{\text{grid,in}}^{\text{FCR}}(t)+P_{\text{bat,out}}^{\text{FCR}}(t)-P_{\text{bat,in}}^{\text{FCR}}(t)-P_{\text{curt}}^{\text{FCR}}(t) \quad \forall t. \tag{8}$$

Please note that the time step length for SC (in our setting $\Delta t = 0.25\,\text{h}$) may differ from that of an FCR period (in our setting $\Delta t^{\text{FCR}} = 4\,\text{h}$). We therefore need to define a function mapping the SC time steps to the respective FCR time steps:

$$t^{\text{FCR}} := \left\lceil t \cdot \frac{\Delta t}{\Delta t^{\text{FCR}}} \right\rceil. \tag{9}$$

The different time resolution for SC and FCR provision implies that the share of the battery power that is reserved for FCR needs to be identical for all SC time steps that are part of the same FCR period:

$$\lambda^{\text{FCR}}(t) = \tilde{\lambda}^{\text{FCR}}(t^{\text{FCR}}) \quad \forall t. \tag{10}$$

Moreover, the remuneration for FCR provision is paid per FCR period and consequently needs to be split among all corresponding SC time steps:

$$c^{\text{FCR}}(t) = \tilde{c}^{\text{FCR}}(t^{\text{FCR}}) \cdot \frac{\Delta t}{\Delta t^{\text{FCR}}} \quad \forall t. \tag{11}$$

Finally, lower and upper bounds for the different decision variables need to be defined, which are outlined in the following.

The share of the battery that is used for FCR provision is limited to 100 %, i.e., in the most extreme case, the battery would not be available to increase SC in the respective time period:

$$0 \leq \lambda^{\text{FCR}}(t) \leq 1 \quad \forall t. \tag{12}$$

Only the fraction of the battery power not reserved for FCR provision is available to increase the household's SC by charging and discharging the battery:

$$0 \leq P_{\text{bat,in}}^{\text{SC}}(t) \leq \left(1-\lambda^{\text{FCR}}(t)\right) \cdot P_{\text{bat}}^{\max} \quad \forall t, \tag{13}$$

$$0 \leq P^{\mathrm{SC}}_{\mathrm{bat,out}}(t) \leq \left(1 - \lambda^{\mathrm{FCR}}(t)\right) \cdot P^{\max}_{\mathrm{bat}} \quad \forall t. \tag{14}$$

Analogously, only the fraction of the battery power reserved specifically for FCR is available to provide negative (positive) FCR by charging (discharging) the battery:

$$0 \leq P^{\mathrm{FCR}}_{\mathrm{bat,in}}(t) \leq \lambda^{\mathrm{FCR}}(t) \cdot P^{\max}_{\mathrm{bat}} \quad \forall t, \tag{15}$$

$$0 \leq P^{\mathrm{FCR}}_{\mathrm{bat,out}}(t) \leq \lambda^{\mathrm{FCR}}(t) \cdot P^{\max}_{\mathrm{bat}} \quad \forall t. \tag{16}$$

Moreover, the SOC of the battery may not exceed the available storage volume:

$$0 \leq E^{\mathrm{total}}_{\mathrm{bat}}(t) \leq E^{\max}_{\mathrm{bat}} \quad \forall t. \tag{17}$$

Finally, as previously mentioned, the artificial SOC is subject to other bounds than the actual SOC. This is because a certain fraction of the storage volume needs to be reserved to be able to provide FCR for a minimum time period (in our setting $\tau^{\mathrm{FCR}}_{\min} = 0.25\,\mathrm{h}$):

$$\lambda^{\mathrm{FCR}}(t) \cdot P^{\max}_{\mathrm{bat}} \cdot \Delta\tau^{\mathrm{FCR}}_{\min} \leq E^{\mathrm{SC}}_{\mathrm{bat}}(t) \leq E^{\max}_{\mathrm{bat}} - \lambda^{\mathrm{FCR}}(t) \cdot P^{\max}_{\mathrm{bat}} \cdot \Delta\tau^{\mathrm{FCR}}_{\min} \quad \forall t. \tag{18}$$

4.2 Data and assumptions

An overview of the main input data and assumptions used for this paper can be found in Table 1.

As previously mentioned, we take a household perspective. Minimum bid sizes (1 MW, see Section 2) are not considered, but in line with Gomez-Gonzalez et al. (2020), we assume a 20 % share in revenues for the aggregator. To account for the heterogeneity of households and in order to avoid biases caused by aggregated or synthesized data, we use empirically measured household load profiles (Quoilin et al., 2016; Schopfer et al., 2018; Fett et al., 2019). Figure 1 shows the peak load and yearly electricity consumption of these load profiles. The optimization model is then run for a whole year for each of the 162 load profiles, which increases the robustness of the results.

Table 1: Overview of the input data and assumptions.

Model parameter	Unit	Value	Sources
Model characteristics			
Empirical household profiles	#	162	Tjaden et al. (2015); Kaschub (2017)
Simulation time step	h	0.25	Kaschub et al. (2016)
Optimization horizon	a	1	Gomez-Gonzalez et al. (2020)
Photovoltaics and battery storage			
PV size per HH	kW_p	data set	Fett et al. (2021)
Specific annual yield	kWh/kW_p	1087	Kaschub (2017)
Storage size per HH	kWh	data set	Fett et al. (2021)
Energy-to-power ratio	kWh/kW	1	Kaschub et al. (2016)
Round-trip efficiency	%	88	Fett et al. (2019)
Cost and remuneration of electricity			
Household electricity price	EUR/kWh	0.32	Bundesverband der Energie- und Wasserwirtschaft (2022)
Feed-in tariff	EUR/kWh	0.08	Bundesverband Solarwirtschaft (2022)
Frequency containment reserve			
FCR price	EUR/MW/4 h	time series	German Transmission Grid Operators: 50 Hertz, Amprion, Tennet, TransnetBW (2022a)
Grid frequency	Hz	time series	50Hertz (2022)
Aggregator's share of revenue	%	20	Gomez-Gonzalez et al. (2020)

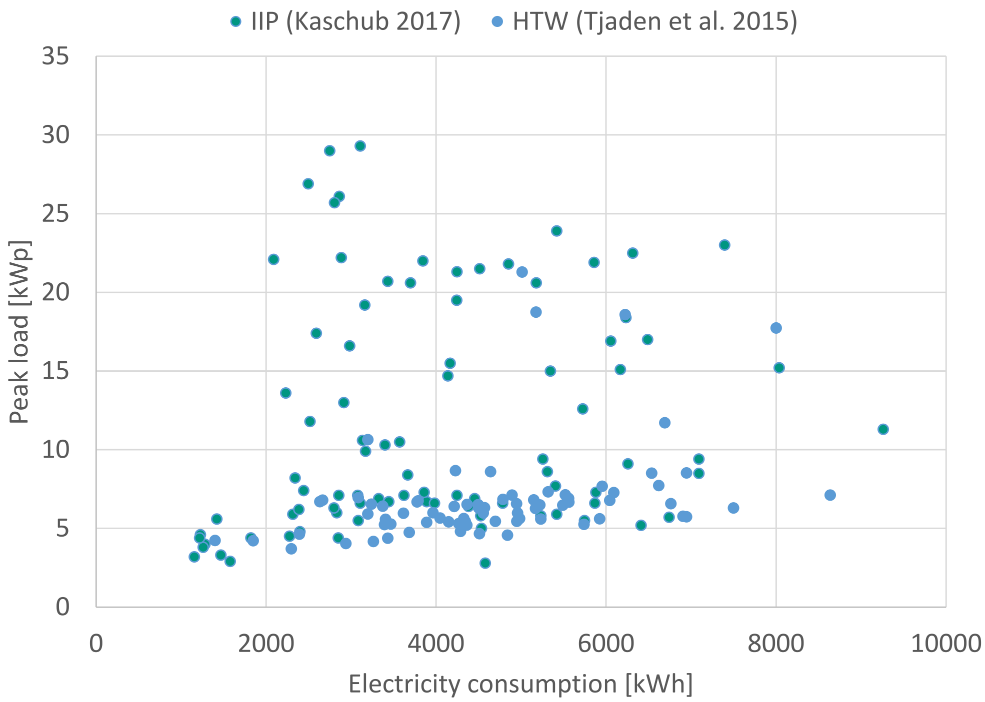

Figure 1: Yearly electricity consumption and peak load of the household load curves.

Furthermore, revenues from FCR are not taken into account for the investment and sizing of PV and BSSs, because FCR prices and regulations have been highly volatile in the past years and consequently there are no long-term forecasts for FCR prices. Therefore we use the PV and battery sizes for the year 2020 from a previous paper (Fett et al., 2021). There, a net present value (NPV) based approach is used to determine the optimal system configuration for each of the 162 households. All electricity related costs including investment in PV and BSS, expenditures for electricity, and income from PV feed-in remuneration are considered. Moreover, it is assumed that households behave economically rational and and have a fixed investment horizon of 20 years (the period of the guaranteed feed-in tariff for PV installations in Germany). The resulting average size of the BSS is 2.6 ± 1.2 kWh. For more details, please check the original publication.

As previously mentioned, FCR prices are very volatile. Still, between 2015 and early 2021 a general downward trend in FCR prices can be observed. Average FCR prices dropped from 3600 EUR/MW/week to less than 1500 EUR/MW/week (Figgener et al., 2022b). One of the main drivers of this development was the increasing number of utility-scale BSSs (Figgener et al., 2022a). In line with other energy markets, FCR prices rose drastically from the second half of 2021, due to uncertainty regarding Russian gas supply and the war in Ukraine. FCR prices reached up to 9000 EUR/MW/week by the end of 2021 and still ranged between 2000 EUR/MW/week and 6000 EUR/MW/week in 2022 (Figgener et al., 2022b). In this paper, we decided to depict "a normal situation", therefore we use the FCR prices from July 2020 through June 2021, because at this point the 4h service periods were already introduced (see Section 2), but prices were still following previous trends. The same applies to the household electricity prices, which are in line with tariffs at the end of 2021, but strongly increased afterwards (Bundesverband der Energie- und Wasserwirtschaft, 2022).

5 Results and Discussion

In the following, we present and discuss the findings of our analyses. First, the considered scenarios are introduced in Section 5.1. Then, our results are shown in Section 5.2 and a sensitivity analysis is provided in Section 5.3.

5.1 Scenarios

In order to evaluate the joint provision of FCR and SC enhancement, we consider the following scenarios:

1. *SC* – the current standard for most German households, where the BSS is only used to increase SC.
2. *Fixed* – fixed shares of 10 % or 20 % of the BSS are used for FCR. The use of fixed shares is the current standard in literature and existing business models (see Section 3). This scenario is used as a benchmark case.
3. *Prio* – the revenues from FCR are weighted with a penalty term of only 5 %, so that FCR is almost exclusively provided during idle times of the BSS and SC is prioritized.
4. *Opt* – savings from SC and revenues from FCR are jointly optimized.

5.2 Results

The box plots in Figure 2 show the additional financial gains of all 162 considered households as compared to the case of only using the BSS for self-consumption. For this and all the following box plots, the boxes represent the data for the lower quartile, the median, and the upper quartile of the investigated households; the x the means; and the whiskers the households with the minimum and maximum additional gains, respectively. As can be seen, reserving a constant share of either 10 % or 20 % of the BSS for FCR provision (*Fixed*) only leads to minimal additional financial benefits as compared to the scenario, where the storage is exclusively used for self-consumption (*SC*). In contrast to this, a joint optimization of SC and FCR provision (*Opt*) leads to average additional yearly gains of more than 65 EUR per household. As can be seen, there is substantial variation between households. Nevertheless, around two thirds of the households can gain at least 50 EUR per year. Remarkably, also the scenario where SC is prioritized (*Prio*) leads to significant additional gains, which are only slightly lower than in *Opt*. To put these additional gains into perspective, on average the increased SC due to the BSS results in savings of about 200 EUR per household. Therefore, average additional gains of more than 25 % can be obtained in scenarios *Opt* and *Prio*.

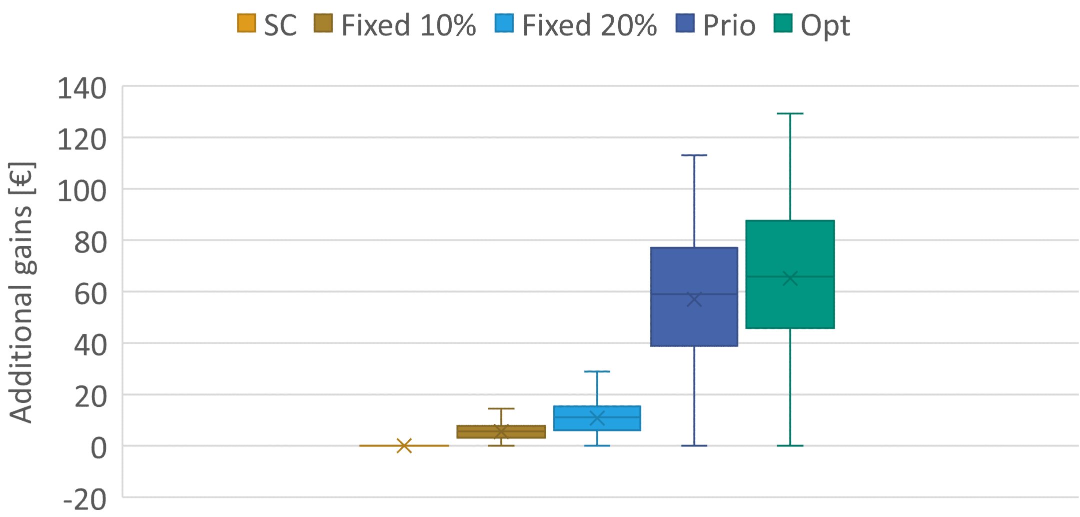

Figure 2: Additional gains in comparison with only SC in the different scenarios.

By using fixed shares of the BSS for FCR and thereby neglecting the seasonal fluctuations in the utilization of the BSS and the flexibility provided by the updated regulation, most works in the literature underestimate the potentials of FCR from residential BSS.

The average shares of the BSS reserved for FCR are shown in Figure 3. The shares for *Fixed* and *SC* are part of the scenario definitions. It is however interesting, that even in *Prio*, average FCR shares are quite high. They range between 34 % and 48 % for the different households, with two thirds of the households reaching yearly average FCR shares of more than 40 %. There is only a moderate increase in scenario *Opt*, where all values are about 10 % higher. A more detailed analysis of the share of the BSS used for FCR reveals that the highest shares in *Prio* (above 40 %) are reached in autumn and especially winter. A supplementary linear regression analysis confirms a relationship between monthly PV generation and average monthly FCR share ($R^2 = 0.57$).

Only small losses in self-sufficiency levels can be observed across all scenarios (see Figure 4). As can be expected, prioritizing SC (*Prio*) leads to the lowest losses in self-sufficiency rate, which are almost nonexistent. Also *Opt* only results in minimal losses, which are still smaller than in *Fixed* with 10 % of the BSS reserved for FCR.

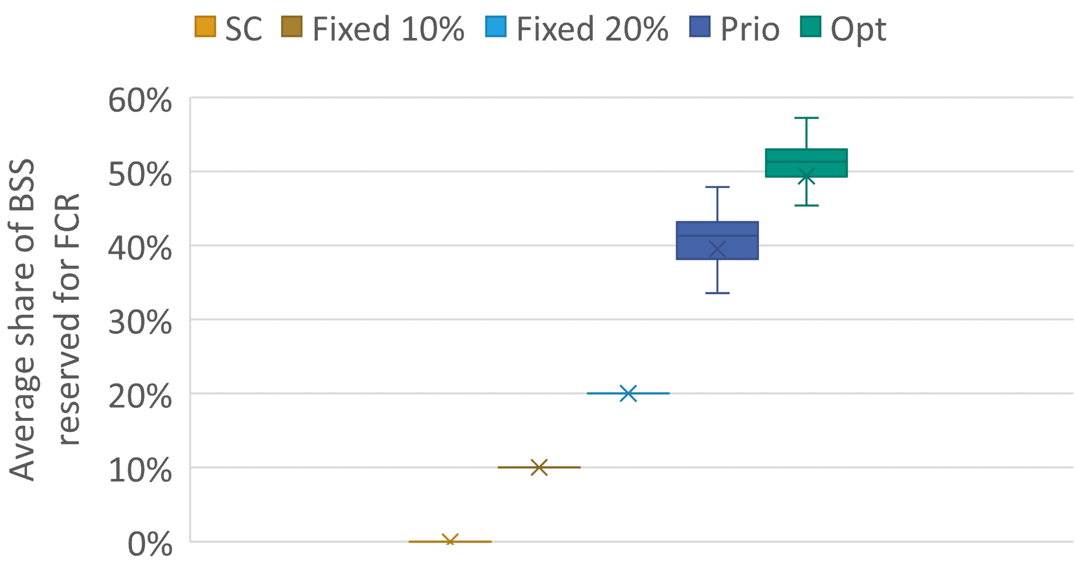

Figure 3: Share of BSS reserved for FCR in the different scenarios.

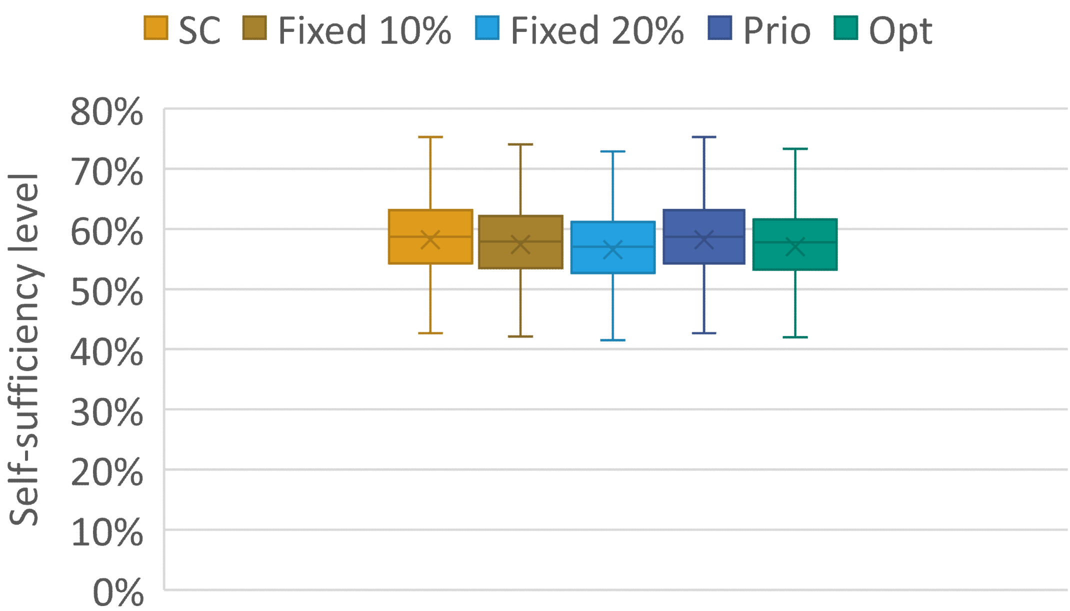

Figure 4: Self-sufficiency levels in the different scenarios.

5.3 Sensitivity Analysis

Additional to the scenarios previously presented, we conduct a sensitivity analysis to verify the robustness of our results.

It can be observed, that in reality residential BSSs are often larger than they would be purely based on profitability (Figgener et al., 2018). Therefore, we first examine how doubling the storage sizes (the energy-to-power ratio remains unchanged) influences the results in scenarios *SC_X2*, *Prio_X2*, and *Opt_X2*.

As explained in Section 4.2, electricity and FCR prices are currently drastically elevated. Consequently, we also evaluate how doubling the FCR prices (while maintaining the diurnal and seasonal fluctuations) influences the outcomes in scenario *Opt_XP2*.

Finally, the effects of increasing household electricity prices to 0.40 EUR/kWh, the current maximum guaranteed by the German government (Bundesverband der Energie- und Wasserwirtschaft, 2022), are analysed in scenario *Opt_EP40*. Since scenario *Prio* can already be considered equivalent to a drastic reduction of FCR prices to 5 %, no additional scenarios with lower FCR prices are included.

The results of the sensitivity analysis are shown in Figures 5–7. Doubling the storage sizes has a stronger effect on both the increase in average FCR shares (8 % vs. 6 %) as well as in additional gains (factor 2.5 vs. 2.4) for *Prio_X2* as compared to *Opt_X2*. Compared with the scenario, where the storage is exclusively used for self-consumption (*SC_X2*), there is still almost no loss in self-sufficiency in scenario *Prio_X2*, while the loss in scenario *Opt_X2* remains very small.

Doubling the FCR prices also more than doubles the additional gains in *Prio_XP2*. The average FCR shares increase stronger than in the other scenarios by more than 12 %. Since the self-sufficiency level decreases stronger than before, it can be concluded that a little autarky is given up in order to increase the gains from FCR.

An increase of the household electricity price by 25 % to 0.40 EUR/kWh only has small effects. The average FCR shares in *Opt_EP40* decrease by about 3.5 %, leading to a small decrease in additional gains and a slight increase in self-sufficiency.

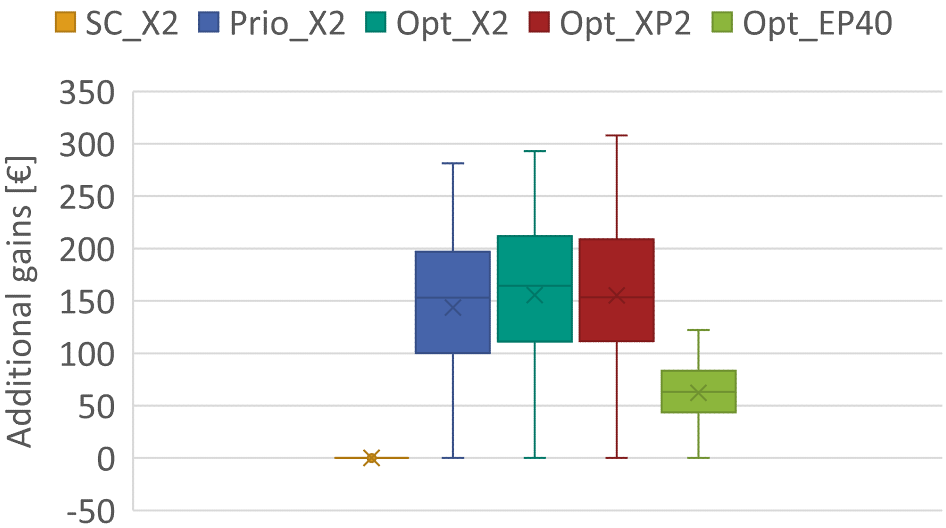

Figure 5: Additional gains in comparison with only SC in the different scenarios of the sensitivity analysis.

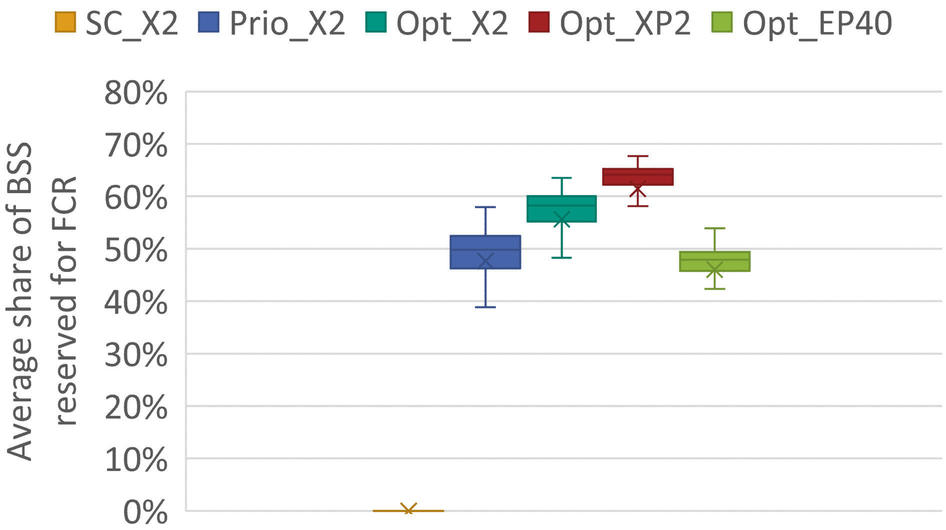

Figure 6: Share of BSS reserved for FCR in the different scenarios of the sensitivity analysis.

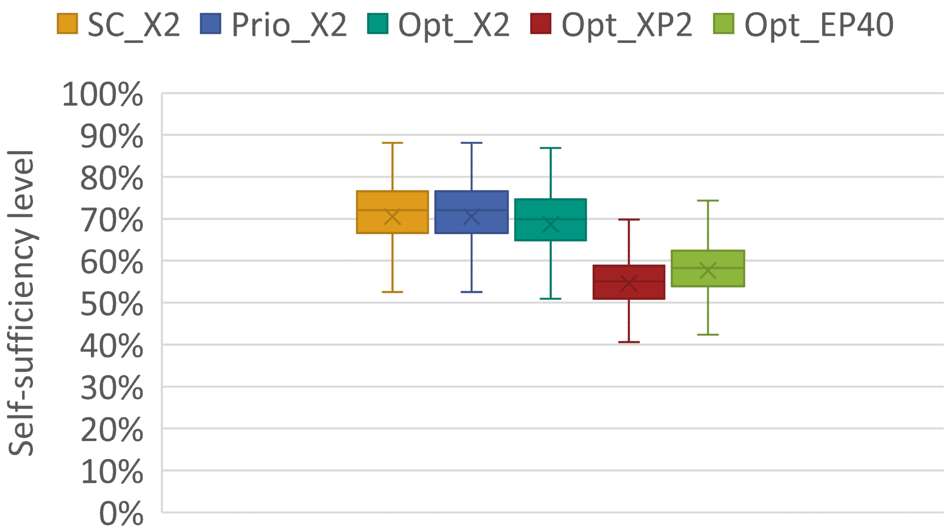

Figure 7: Share of BSS reserved for FCR in the different scenarios of the sensitivity analysis.

6 Limitations

Despite the considerable modeling effort, our work has certain limitations, which we briefly address and discuss in the following.

We do not account for additional battery aging caused by FCR provision, but the publication from which the battery sizes were taken, oversizes the batteries by 20 % to account for battery degradation (Fett et al., 2021; Kaschub, 2017). In general, a higher FCR share results in a higher average SOC which in turn increases calenderic battery aging (Angenendt et al., 2020). The changes in battery lifetime are however quite small, e.g. an FCR share of 50 % results in an increase of battery aging by less than 2 % (Angenendt et al., 2020). Cycle aging is reduced with increasing FCR shares as part of the battery capacity cannot be used for SC anymore (Angenendt et al., 2020). Summing up, the authors only find small effects on battery lifetime, which is also in line with the findings of Gomez-Gonzalez et al. (2020) and Maeyaert et al. (2020).

As the focus of our publication are households, two simplifications are made with regard to the aggregator. First, we assume that the minimum bid size of 1 MW is always met. Second, it is assumed that all FCR bids are accepted. Due to the introduction of uniform pricing (see Section 2) and the low (opportunity) costs for providing FCR from residential BSS (cf. scenario *PRIO*), the latter should not have a big impact, as low bids would be possible.

The optimization model presented in this paper uses perfect foresight for the forecasts of PV generation, electricity demand and FCR prices, which leads to optimal benefits from the joint provision of FCR and SC. In reality, a rolling horizon optimization could be used (Englberger et al., 2020), which would lead to lower benefits. The recent changes in regulation have however reduced the impact of forecasting errors. As previously mentioned, the introduction of uniform pricing allows for low bids, reducing the impact of price forecasting errors. Shorter service and lead times facilitate the forecasts of PV generation and electricity demand, which can e.g. be done with comparably high accuracy with the adaptive persistence forecast (Bergner et al., 2015).

7 Conclusion and Policy Implications

In this article, we analyzed the potential for the joint provision of FCR and SC increase from residential BSSs. A linear optimization model was developed and applied to 162 individual household load curves with varying system configurations. Thereby, newly introduced regulation, the actual activation of FCR and seasonal fluctuations in the utilization of the BSS for SC were considered. Different scenarios including the joint optimization of earnings from FCR and SC increase were examined. An analysis with such a level of detail is unique in the literature to date and provides important additional insights on the potential of FCR provision from residential BSSs.

Our results show that joint provision of FCR and SC can indeed increase the profitability of residential BSSs. This is especially true, when instead of reserving a fixed share of the BSS for FCR, the FCR shares are optimized dynamically using the flexibility given by recent regulation.

A different benefit of the dynamic optimization of the FCR share are smaller losses in SC, despite comparably high shares of FCR. Even though the average yearly FCR share is more than doubled, the SC losses are still lower.

Moreover, the results emphasize the importance of analyzing a variety of different households, as there is significant variation in both the average FCR share as well as the profitability. Nonetheless, two thirds of household can increase the economic benefits of the battery storage by at least 25 %.

By 2021, more than 400 thousand residential BSSs with a capacity of 3.5 GWh and a rated power of 1.9 GW are installed in Germany (Figgener et al., 2022a). The size of the German FCR market is only around 600 MW. Given the average FCR share of almost 40 % in the scenario where SC is prioritized (*Prio*), the FCR market could be completely covered by residential BSSs.

An increasing number of market participants would probably lead to decreasing prices. FCR prices were already reduced by 95 % in *Prio*, showing that FCR could still be offered even when prices are very low. Important factors for the realization of the FCR potential from residential BSSs are the costs for measurement and market participation, which are determined by regulatory requirements. Despite an increasing profitability for residential BSSs, favorable regulation, e.g. if not every single household has to be monitored separately (Angenendt et al., 2020), could also lead to decreasing costs for FCR provision. As the costs for FCR provision are reallocated through the grid charges, this would in turn also lead to decreasing electricity prices.

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