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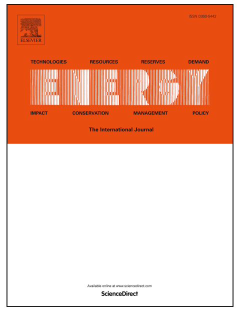

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Providing frequency control reserve with photovoltaic battery energy storage systems and power-to-heat coupling

Georg Angenendt[1,2,3], Sebastian Zurmühlen[1,2,3], Jan Figgener[1,2,3],Kai-Philipp Kairies[1,2,3], Dirk Uwe Sauer[1,2,3]

[1] Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Germany
[2] Juelich Aachen Research Alliance, JARA-Energy, Germany
[3] Institute for Power Generation and Storage Systems (PGS), RWTH Aachen University, Germany

Abstract

The number of households with photovoltaic battery storage systems is steadily growing, and so is the number of heat pump installations. An integrated home combines domestic battery systems and a heat pump for power-to-heat coupling. During winter, storage systems in an integrated home are not used to their full capacity due to low solar radiation. This potential can be used to enhance the economics by applying a dual-use scheme. In this publication, an integrated home that participates in the frequency control reserve market is investigated.

A major advantage of integrated homes with power-to-heat coupling in comparison to standalone battery storages is the additional flexibility to absorb negative control reserve power in the heating sector. Seasonal variation of feed-in from photovoltaics is considered by an advanced strategy for variable provision of control reserve.

Results show that a dual-use operation with participation in the control reserve market can increase the profitability of storage systems. Market participation leads to accelerated battery aging, mainly driven by increased calendar aging. This is overcompensated by the possible incomes. Under consideration of low costs for market participation, a constant provision of at least three kilowatts of reserve power could be economical. A variable provision further enhances economic efficiency.

Keywords: photovoltaics; battery energy storage systems; power-to-heat coupling; frequency control reserve market; heat pump; operation

Nomenclature

A	annuity
Ah	ampere hour
aFRR	automatic frequency restauration reserve
a_{FCR}	frequency control reserve factor
BESS	battery energy storage system
DC	direct current
DHW	domestic hot water
DSO	distribution system operator
E	energy
E/P	energy to power ratio
ENTSO-E	European Network of Transmission System Operators for Electricity
FCR	frequency control reserve
NMC	Nickel Manganese Cobalt Oxide
P	power
P2H	Power-toheat
P-f	power- frequency
PV	photovoltaic
SC	self-consumption
SOC	state of charge
SOH	state of health
TCR	tertiary control reserve
TSO	transmission system operator

1 Introduction

1.1 Motivation

The Paris agreement aims to reduce the greenhouse gas emissions in order to reduce the risks and impacts of climate change [1]. Therefore, the expansion of renewable energies is requested.

The growing share of renewable energies [2] leads to a growing fluctuation of the feed-in power and therefore growing needs for flexibility option. Even though the need for control reserve in Central Europe remained constant in recent years [3]. Battery energy systems can provide these flexibility options in the power transport grid, either at grid level or distributed [4]. Distributed battery energy storage systems (BESS) can provide control reserve, if connected to a virtual power plant [5]. Distributed battery energy storage systems are often located in residential households in combination with photovoltaic (PV) power plants and are used to enhance the self-consumption from the PV power plant [6].

Furthermore, distributed battery systems can be applied in combination with a heat pump in residential buildings [7] and office buildings [8]. Integrated homes combine PV BESS with heat pumps to use the PV power in the heating sector. Due to the sector coupling in integrated homes, renewable energies can be used for heating and contribute to the decarbonisation process of the heating sector [9]. Germany is facing a continuous growth of residential PV BESS [10] and heat pumps [11]. A contribution in the control reserve market could support the pathway for further integration of renewable energies and generate additional revenues [12]. Residential home storage systems aggregated to a virtual power plant can participate in the control reserve market as pointed out in section 2.3. Additional revenues can be generated especially in winter months, when the battery is only slightly used for home storage operation. These additional revenues can support the market penetration of integrated homes. Besides enhanced economics, a participation in the control reserve market could support the grid stabilization and therefore enable potential for further integration of renewable energies.

In Central Europe, the frequency control reserve (FCR) market is a promising market for integrated homes, because it has the lowest requirements regarding the energy-to-power ratio of participating storage units. A major advantage of integrated homes with power-to-heat coupling in comparison to standalone battery storage is the additional flexibility to absorb the negative control reserve power in the heating sector. This allows an extension of the operating limits of a power-to-heat coupled battery. The heating rod is used, to transfer the FCR power to the heating sector. This paper investigates integrated homes providing control reserve and the influence on the home storage operation as well as the influence on battery aging. Revenues from the market participation are taken into account as well as additional savings due to the use of the so-called degrees of freedom for provision of frequency control reserve. Advantages of integrated homes in comparison to standalone battery systems, due to the flexibility from the heating sector, are presented.

This publication is based on a conference paper [13] and advances the journal paper [9]. In addition to the conference paper, a FCR bidding strategy is presented to offer FCR power season-dependent. Furthermore, it details the mathematics behind the developed strategies and compares them to commonly used methods.

1.2 Literature review

The participation of battery storage systems on frequency control reserve markets is wildly discussed in literature. However, the literature mainly focuses on grid-scale battery systems. Aggregated residential battery systems participating on the control reserve market is a relatively new topic and therefore, literature is still weak. This literature review is focused on battery system participating on the control reserve market.

In [4] a analysis of markets for grid connected BESS is presented. The publication concludes that the penetration of the control reserve markets depends on the economic performance of the energy storage systems. The FCR market could be a promising market.

[14] presents an operation strategy for battery storage systems participating in the FCR market. The publication concludes, that the installation site and the choice of the energy to power ratio have a higher impact on the economics of the storage system.

In [15] the optimal provision of primary frequency control with battery systems is investigated. Therefore, the degrees of freedom are described, and the effect of their utilization on battery system operation is analyzed. Additionally in [16] the billing and measuring issues as well as the current regulatory framework conditions in Germany are discussed.

The impact of different operation strategies for battery energy storage systems providing frequency control reserve is analyzed in [17]. The consideration of price trends and bidding strategies are added in [18]. The publication concludes that under the assumption of a moderate FCR price drop, BESS prices and lifetimes and the time of investment are crucial for the investment's attractiveness.

A technical, operational and regulatory suitability of battery energy storage systems (BESS) to bid into the European ancillary market is investigated in [19]. The results from the operation of the Zurich 1 MW BESS in this market are presented.

The fundamentals of using battery energy storage systems to provide primary control reserves in Germany are discussed in [20]. In this publication, the combination with PV systems is discussed as well.

Caterva (Today: Alelion Energy Systems GmbH), Ampard AG (Lichtblick) and sonnen eServices GmbH are aggregators of PV-BESS, which are prequalified in the German FCR market [21]. Connected to a virtual battery, these PV-BESS can provide FCR [22].

Melo et al. [23] investigated FCR provided by hybrid battery storage and power-to-heat system. He points out the advantages of hybrid systems and concludes that the economic can be improved using systems with a capacity-power ratio lower than one. Nevertheless, the studied system is not economical feasible under current electricity prices. Domestic battery systems with power-to-heat coupling participating on the FCR market are investigated in [24]. The publication concluded that savings up to 31 % in comparison to a BESS without P2H and FCR are possible. In comparison to the publication at hand, publication [24] does not use an aging model for BESS. Furthermore, different strategies for FCR offers are not investigated. Publication [25] investigated the provision of BESS with power-to-heat coupling on MW scale. PV home storages participating on the FCR market are investigated in [26]. The authors conclude that a PV-BESS, which combines enhancement of PV self-consumption with the provision of frequency restoration reserves leads to profitable investments. A power-to-heat coupling is not investigated in this publication. Engels et al. investigate BESS for self-consumption and provision of frequency control reserve. The authors conclude that revenues of storage systems that combine self-consumption with provision of frequency control reserve increases significantly [27].

The combination of peak shaving operation and frequency regulation with BESS is investigated in [28]. The results suggest that batteries can achieve a higher economic benefit, when combining both applications. Janßen analyses the operation of PV battery energy storage system in combination with frequency control reserve [29] and reveals that the provision of frequency control reserve is not economic feasible.

Residential PV BESS participating on the frequency control reserve market is an emerging topic. This publication presents the advantages of residential battery systems participating in the market when using heat pumps. The combination of residential BESS with power-to-heat coupling participating on the frequency control reserve market is not discussed in detail in literature so far, even though the combination offers many advantages. This is why the publication at hand fills a gap in literature. In addition, a new season-dependent bidding strategy for the aggregated residential BESS participating in the FCR market is presented.

This is especially relevant for manufacturers of residential battery systems and operators of virtual power plants, who search for new market opportunities. The publication helps to understand the influence of additional FCR market participation on aggregated residential BESS, since the effects on battery aging, operation and self-consumption rate are analyzed.

2 Frequency control reserve with battery energy storage systems

Understanding of the frequency control reserve (FCR) market in Central Europe is necessary to adapt the energy management system of the integrated home. In the following, the FCR market and the requirements are presented in detail. The requirements are given by the TSO's and are presented in [5]. The Central European FCR market has to be delivered between a frequency deviation of + 200 mHz and - 200 mHz. This regulation is published in [5] and discussed in numerous publications [14, 16, 17] as presented in the introduction. Each participant in the FCR market has to follow the P-f characteristic curve shown in Figure 1. As long as the frequency is between 49.99 to 50.01 Hz no action must be taken. This frequency range is called dead band. If the frequency deviation violates this window, an activation call made by the TSO is performed (automatically and decentralized, according to P-f characteristic curve). For larger deviations (±10 mHz to ±200 mHz) the FCR power should be delivered and increased linearly up to 100 % of the bid amount and maintain constant at its maximum as long as the frequency deviation is larger than ±200 mHz [20].

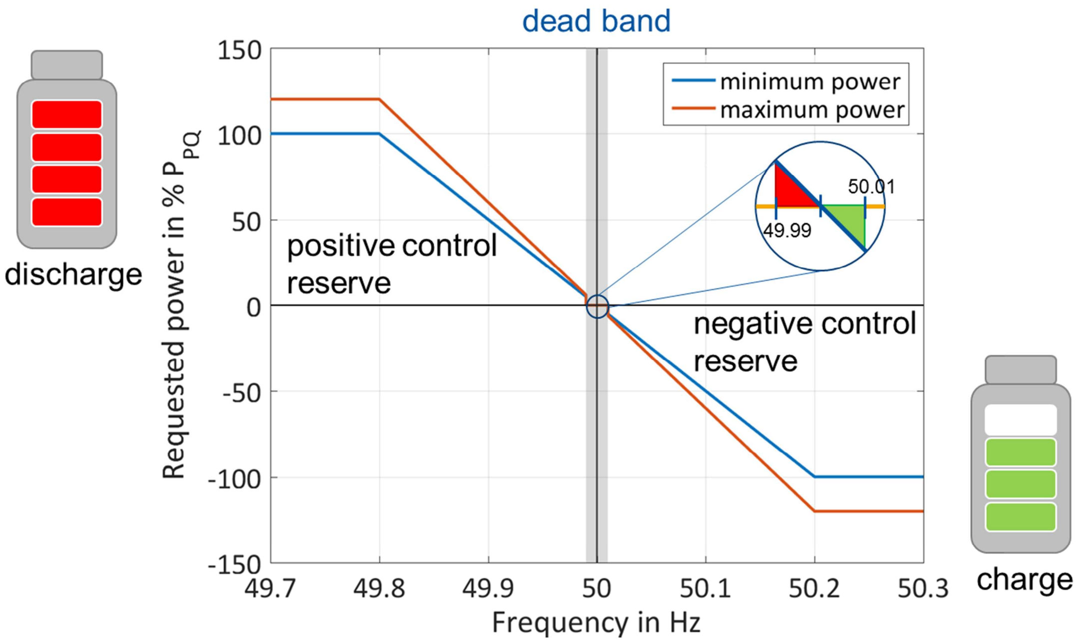

Figure 1: Power to frequency characteristic (P-f characteristics) for BESS providing FCR on the Central European market. The maximum power is the maximum power, which can be provided in the case of over-fulfillment and minimum power depicts the minimum power, which can be provided in the case of under-fulfillment.

Figure 1 presents the FCR P-f characteristics curve for a battery energy storage system (BESS). This figure illustrates the delivery requirements of the FCR. If the frequency violates the standard operation situation and the deviation is between 10 mHz and 200 mHz the

BESS should start to absorb power from the grid (charging the batteries). The standard operation situation is illustrated in Figure 3. The amount of power should increase linearly with an increase of the grid frequency between 10 mHz and 200 mHz and remain at its maximum if a deviation remains above 200 mHz. For a negative deviation, the behavior is the same, except that BESS should discharge and feed power into the grid. To ensure that BESS are able to deliver the required power they have to undergo the prequalification process.

Prequalification of the battery energy storage system

Battery energy storage systems need to be prequalified in order to participate in the FCR market. The minimum amount of power that the BESS should provide is 1 MW for 15 minutes, twice. All requirements regarding power ratings or minimum delivery time are formulated by the responsible TSOs. The requirements assumed in this paper are given by the German TSOs [5]. Figure 2 describes the requirements for prequalification and shows that BESS have to provide FCR for 30 minutes in total. This regulation is called the 30 minute criterion, which states that BESS should be able to provide the prequalified FCR, both charging and discharging, for 30 minutes.

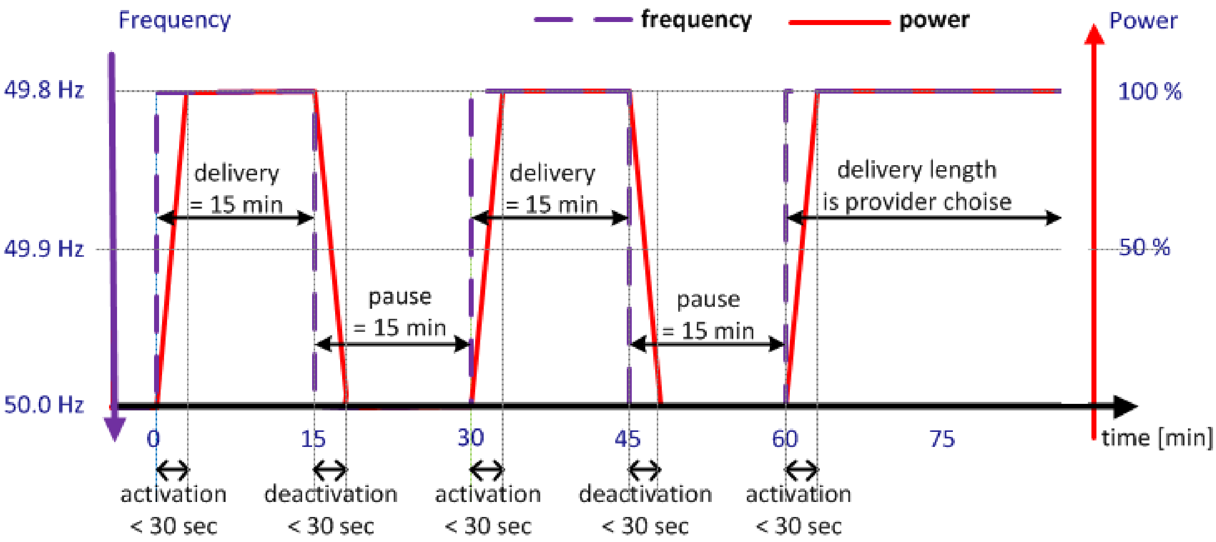

Figure 2: Performance requirements for prequalification of BESS on the Central European FCR market

2.1 Operating range for battery energy storage systems

For a battery system to participate in the FCR market, regulations are given in [5], which defines the compulsory available energy reserve in the storage system.

Considering these rules and the prequalification requirements for BESS, the resulting permitted SOC ranges are shown in Figure 3. E_{bat} (energy content of the battery) and P_{PQ} (prequalified FCR power) determine the maximum and minimum SOC limits. Equations (1) and (2) show these values:

$$SOC_{upper\ boudary} = (E_{bat} - 0.5h \cdot P_{PQ})/E_{bat} \quad (1)$$

$$SOC_{lower\ boudary} = (0.5h \cdot P_{PQ})/E_{bat} \quad (2)$$

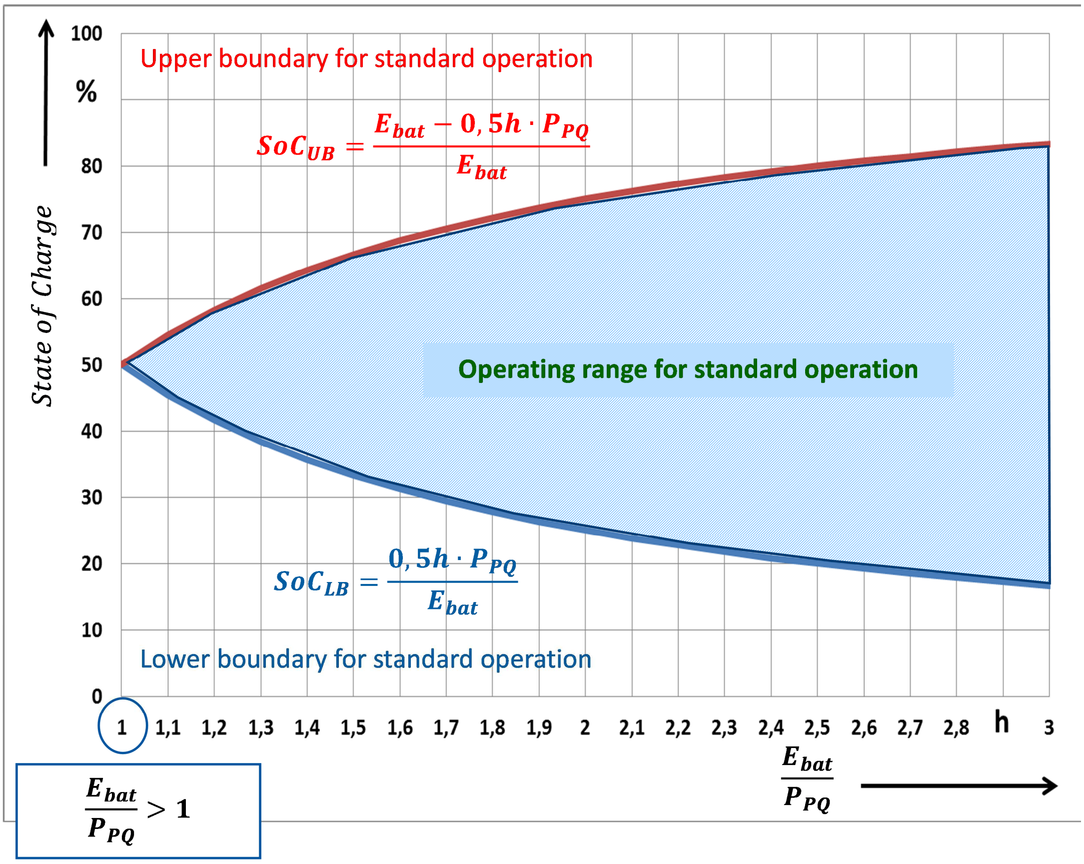

Figure 3: Required state of charge (SOC) range for a battery energy storage system (BESS) based on the 30 min criterion on the Central European FCR market

The 30 min criterion is violated when the operating range does not remain within the operation range for standard operation while the grid is in a standard operation situation. It is a standard operation situation as long as none of the following criteria are fulfilled:

- frequency deviation above ±200 mHz
- frequency deviation above ±100 mHz for more than 5 min
- frequency deviation above ±50 mHz for more than 15 min.

To fulfill these requirements, the available energy of the BESS must be greater than the prequalified power as described in equation (3).

$$E_{bat}/P_{PQ} > 1h \quad (3)$$

In real applications, the available energy has to last for a minimum time of 1.33 hours, because a frequency deviation of 10 minutes at 100 Hz plus a frequency deviation of 5 minutes with 200 Hz is still in the standard operation range. Therefore, a minimum available energy of 40 min in each direction has to be minded. Thus, a total minimum available energy of 1.33 hours is requested in order to get prequalified. Normally 1.5 hours of available energy is used as a boundary, because energy for normal operation and time for recharging has to be minded. For this paper, an available energy rate of 1.43 h is assumed based on the analysis presented in section 3.2.2.

As soon as the frequency reaches the standard operation window, the battery SOC must be restored to the boundary defined in Figure 3. This leads to a limitation of the PV-BESS operation range, if PV-BESS is participating in the FCR market. This limitation is shown in Figure 4.

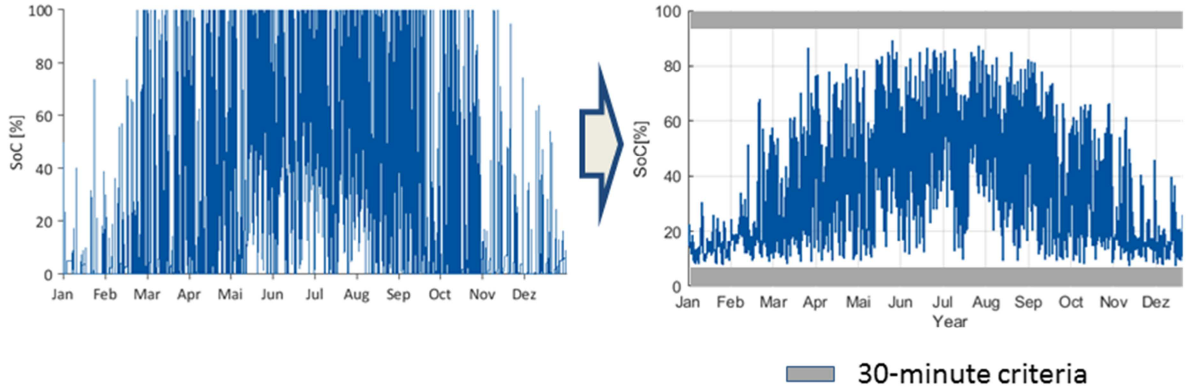

Figure 4: Left: SOC of a 10 kWh PV-BESS without FCR. Right: SOC of a PV-BESS which participating in the FCR market. The 30-minute-criteria is shown, if 1 kW FCR is offered on the market. The presented results are based on simulations.

2.2 Degrees of Freedom

In Central Europe, as defined in [31], TSOs are allowing degrees of freedom in order to keep the battery SOC level within the boundaries defined in Figure 1. These degrees of freedoms are provided considering that FCR participants can slightly deviate from the P-f characteristics curves of Figure 1.

Over fulfillment:

The control power determined by the P-f characteristics curve can be increased by up to 20 % in order to help adjusting the SOC to the required value. The operator of the BESS is allowed to decide if the BESS should be charged or discharged with the additional power [31].

Dead band:

Within the dead band a FCR provider does not have to provide FCR. The operator of the BESS can use this dead band to adjust the SOC of the BESS. Therefore, the control power demand indicated by the P-f characteristic can also be provided within the tolerated deviation range of ±10 mHz if the SOC needs to be adjusted [31]. The SOC adjustment is only allowed if it serves the grid and a maximum power of 5 % of the FCR is allowed. To be able to use the dead band a sufficiently accurate measurement needs to be installed.

Provision Rate:

The control power based on the P-f curve must be provided within 30 seconds or less. This allows the FCR provider to adjust the power gradient in order to influence the SOC.

Scheduled Transactions:

FCR providers can modify the SOC by participating in the electricity market.

2.3 Aggregation of battery energy storage systems

To participate on the FCR market a minimum power of 1 MW is required [32]. This is a boundary for small BESS like PV-BESS, because these systems can only provide FCR of some kilowatts. According to [33], it is allowed to couple these systems in a virtual power plant to provide FCR. These power plants have to be in the same control area [34] and have to undergo the prequalification process as one unit.

As already mentioned, the prequalified power must be supplied for at least 30 minutes. This can be reduced to a 15 minutes criterion [20] if the BESS is operated in a virtual power plant with conventional power plants. This is only allowed if the virtual power planthas no limitation of the available energy. In this case, the virtual power plant has to undergo the prequalification process and an extension of the prequalified power of the virtual power plant is not permitted.

2.4 Prequalification of suppliers

Participants in the control reserve markets have to provide evidence that they can fulfil the technical requirements of providing control reserve power. Therefore, participants have to undergo a technical prequalification process [32]. The prequalification follows the minimum requirements according to the respective transmission code of the responsible TSO. During the prequalification process, the offered prequalified power is checked. The prequalified power is the deployable power change within the activation time, which is 30 seconds for FCR. Furthermore, facilities for control and communication are checked as well.

2.5 Frequency control reserve for photovoltaic home storage systems with power-to-heat coupling

Renewable energy produced by a PV power plant in a household cannot only be used to cover the electric load. This energy can be used to cover the heating demand of the household if for example a heat pump is installed in the building. The examined household in this paper couples the heating sector with the electricity sector to enhance the self-consumption and in some cases the economics of the household [9]. The applied power for heat coupling can be used for the FCR as well. The negative control reserve can be transferred into the heating sector. Therefore, the limitation of the battery can be reduced as depicted in Figure 5. If the BESS is fully charged the negative FCR power can be transferred into the heating sector with the heater rod. The negative FCR has to be used for heating. It is not allowed to waste the negative FCR power.

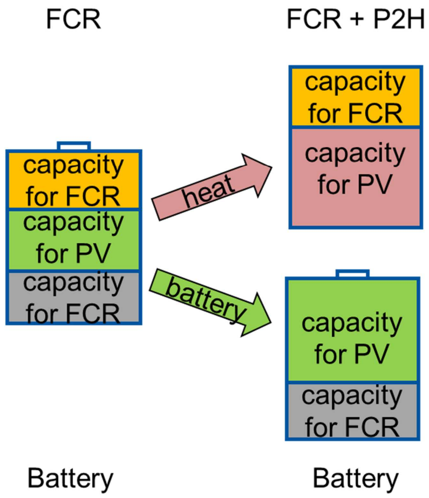

Figure 5: Allocation of the reserve capacity of a BESS with power-to-heat coupling participation in the Central European FCR market in comparison to a standalone BESS. Positive control reserve can be transferred in the heating sector, leading to higher useable capacity.

3 Modeling

The assumptions presented in section 2 apply to all kinds of battery storages participating in the frequency control reserve market. In following, the model of a residential home storage system participating in the frequency control reserve market is introduced and the operation of the home storage system is adjusted to meet the requirements of the frequency control reserve. The requirements to participate in the FCR market presented in section 2 are formulated by the responsible TSOs and apply regardless of the sizing and the type of storage. Thus, the operation strategy of a storage system has to be developed for each specific mode of operation. This is why the operation adjustments of a home storage system are different compared to a those of a community battery storage system, for example. In this publication, we focus on residential home storage systems.

3.1 Model of the integrated home

To evaluate the influence of the participation on the frequency control reserve market with an integrated home a detailed model is used. The integrated home consists of a PV-BESS and a heat system, to provide heating power and domestic hot water (DHW). The electrical system and the heating system are coupled with a heat pump.

The electrical system represents a DC-coupled PV-BESS illustrated in Figure 6. The model has been published and described in great detail in [44]. The model of the PV generator is described in [45] and represents a 10 kWp PV panel parameterized with local dependent radiation data from Lindenberg (Tauche) close to Berlin (Germany) leading to a PV generated energy of 11,400 kWh/a. A load profile to represent the household is applied. The load model offers the consumption data of a German household resulting in an annual consumption of 4,674 kWh [46]. The input data for load and PV radiation have a time resolution of 60 seconds. The thermal demand is calculated based on the irradiation data and the considered model of the household. A frequency profile from Germany with a time resolution of 1 second and accuracy of 0.1 mHz is used. The frequency profile was measured in the *WMEP* project [10]. Furthermore, the energy management system (EMS) and the battery management system (BMS) are represented in the model. The battery model is parameterized with the test results of a cylindrical lithium-nickel-manganese-cobalt-oxide (NMC) 18650 lithium-ion battery cell from LG-Chem (LG ICR18650MF1) with 2.15 Ah. The parameterized aging model is presented in [47].

Different operation strategies of the energy management system are discussed in [47]. The applied operation strategy for the BESS is the maximization of the self-consumption. This operation strategy charges the BESS, when negative residual load is available and discharges the BESS if the residual load is positive.

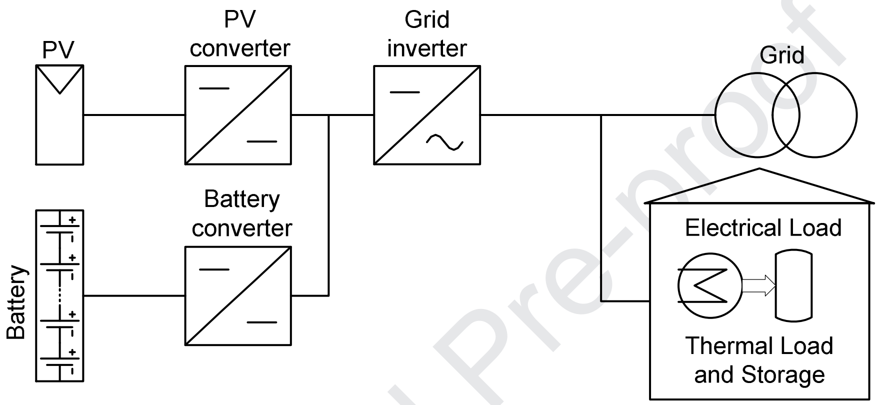

Figure 6: Model of the grid connected DC-coupled PV-BESS with power-to-heat coupling

The thermal part of the model, depicted in Figure 7, is developed and described in [9] and used in [48] and [49]. The heat storages are implemented as a stratified system with five separate layers. The parameterization of the buffer storage is based on a real storage from Schindler und Hoffmann with a 300 liter tank [50]. The DHW Storage is similar to the buffer storage, but additionally the DHW storage contains an electric heater and a heat exchanger. For a four person household, a 300 liter DHW storage is recommended [51]. Therefore, a DHW storage from Schindler und Hofmann is used for parameterization [52]. The building model is based on the “Conventional And Renewable eNergy systems Optimization Toolbox“ (CARNOT) for Matlab/Simulink [53] and represents a Bungalow with 110m² of living area. The heat pump model is based on a Vitocal 200-S heat pump from Vissmann [54] and has a thermal power of 10 $kW_{thermal}$. The seasonal performance factor (SPF) of the heat pump is 3.7, which is close to the upper boundary for air-water heat pumps under real operating conditions according to [55]. Cooling in summer is not considered in the paper at hand, because it is not common in residential buildings in Germany.

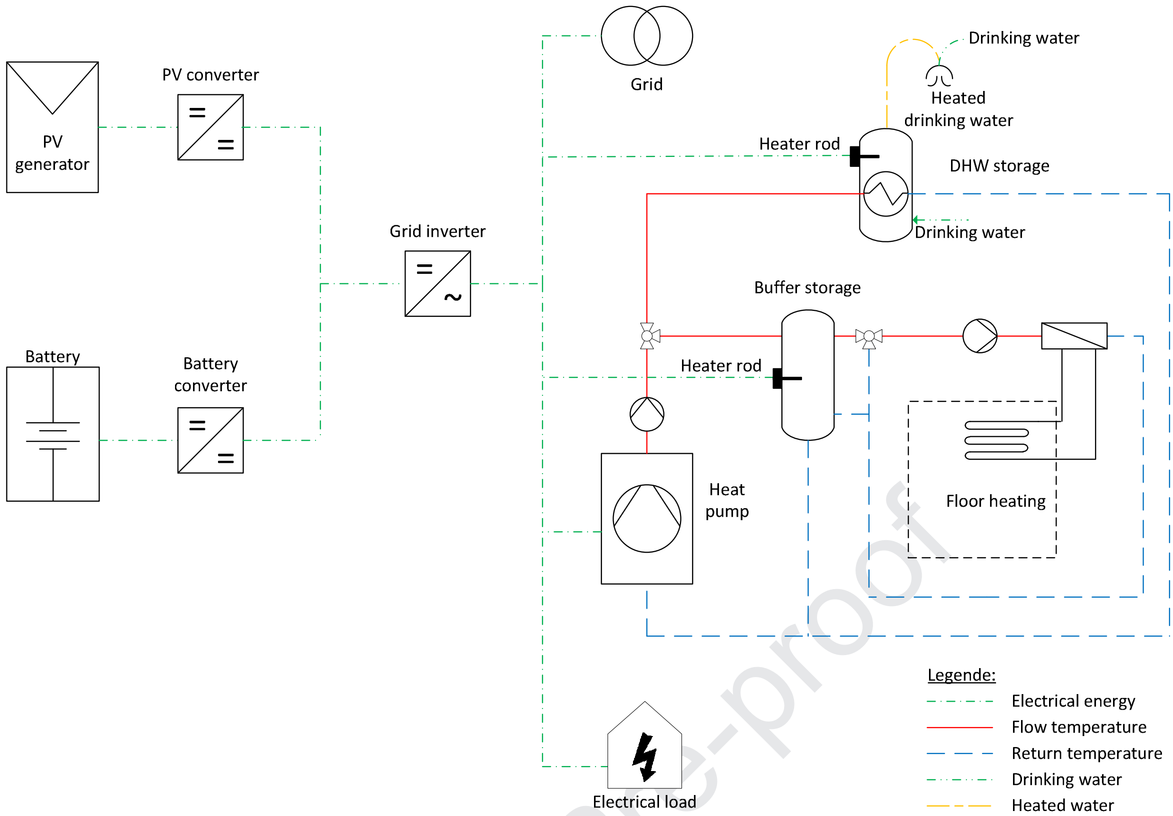

Figure 7: Model of the heating system with a heat pump, DHW storage and buffer storage. This heating system is connected to a PV-BESS.

This presented model is extended to meet the requirements for the FCR market. The adjustments of the model for the FCR market participation are shown in section 3.2. The component sizes for the integrated home participating in the control reserve market are presented in Table 1.

Electric system	size	Heating system	size
PV power plant	10 kW	Heat pump	10 $kW_{thermal}$
Converter sizes	10 kW	DHW storage	300 Liter
Inverter	10 kW	Buffer storage	300 liter
Li-ion battery	10 kWh		

Table 1: Component sizes of the investigated integrated home

3.2 Modell for participating in the frequency control reserve

3.2.1 Adjustment of the scheduled power to guarantee the 30 minute criterion

As described in section 2.1 the 30-minute criteria has to be fulfilled at all times. Therefore, an adjustment of the scheduled power is necessary and the battery has to be recharged on the intraday market. The total time duration for the adjustment of the scheduled power is divided into three 15min time intervals: idle time, lead-time, delivery time.

At the intraday market, transactions can only be made at the beginning of every quarter of hour. Therefore, the maximum time delay between the detection of a scheduled adjustment and transaction on the intraday market is up to 15 minutes. The idle time represents this time delay.
The lead-time represents the time between the transaction and the delivery. The lead-time could be between 15 minutes and 45 minutes [56]. The lead-time is set to the minimum time of 15 minutes in this work, because the possibilities of future inter- virtual power plant energy exchange is considered. The delivery time for intraday transactions is 15 minutes and is considered in this work. The three different time intervals are illustrated in Figure 8.

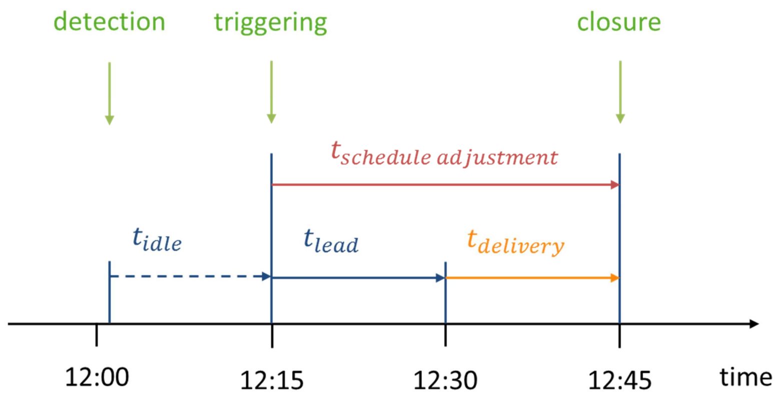

Figure 8: Time line for an adjustment of the scheduled power. After the detection of a schedule adjustment the idle time, lead-time and delivery time has to be minded.

3.2.2 Calculation of the maximum frequency control reserve

To determine the maximum FCR power, which can be offered by the integrated home, every component of the house is analysed separately. The following conditions are derived from requirements proposed by the TSOs and are presented in [5].
The battery must have enough capacity to fulfil the 30-minute criterion. Therefore, schedule adjustments could be necessary. The time delay for a schedule adjustment is calculated in section 3.2.1. The criteria for a standard operation scenario as presented in section 2.1 are minded as well. A worst-case consideration is analysed. Therefore, the time of the detection of a schedule adjustment is set to the second after the quarter-hour boundary for a transaction e.g. 10:00:01 o'clock. During this quarter hour, a frequency deviation of ± 50 mHz is considered. This deviation is valid in the standard operation situation. After this event a frequency deviation of ±200 mHz for 5 minutes is considered, followed by a frequency deviation of ±100 mHz for 10 minutes. These frequency deviations are still defined as the standard operation situation. In this worst case, a violation of the 30-minute criterion is not allowed. For the worst-case, the following frequency deviation after schedule adjustment detection at 10:00:01 o'clock is considered:

1) 10:00:01 till 10:15 frequency deviation of ±50 mHz
2) 10:15 till 10:20 frequency deviation of ±200 mHz
3) 10:20 till 10:30 frequency deviation of ±100 mHz.

After these deviations the 30-minute criterion has still to be fulfilled. In equations (4) to (8), the necessary capacity is calculated.

$$E_1 = 50\ mHz/200\ mHz \cdot 15/60\ h \cdot P_{FCR} = 1/16h \cdot P_{FCR} \quad (4)$$

$$E_2 = 200\ mHz/200\ mHz \cdot 5/60\ h \cdot P_{FCR} = 1/12h \cdot P_{FCR} \quad (5)$$

$$E_3 = 100\ mHz/200\ mHz \cdot 10/60\ h \cdot P_{FCR} = 1/12h \cdot P_{FCR} \quad (6)$$

$$E_4 = 200\ mHz/200\ mHz \cdot 30/60\ h \cdot P_{FCR} = 1/2h \cdot P_{FCR} \quad (7)$$

$$E_{FCR} = E_1 + E_2 + E_3 + E_4 = 0.7292\ h \cdot P_{FCR} \quad (8)$$

With respect to the battery capacity, the energy that needs to be reserved for FCR can be calculated with equation (9).

$$SoC_{FCR} = E_{FCR}/C_{Bat} = 0.7292h/C_{Bat} \cdot P_{FCR} = a_{PCR} \cdot P_{FCR} \quad (9)$$

In this work a 10 kWh battery is considered. Therefore, the factor a_{FCR} for the examined battery system can be calculated with equation (10).

$$a_{FCR} = 0.7292h/C_{Bat} = 0,7292\ h/10\ kWh = 0.073\ 1/kW \quad (10)$$

This leads to a reserved capacity of 7.3 % per kW FCR of a 10 kWh BESS, as presented in equation (11).

$$SoC_{FCR} = 7.3\ \%/kW\ \ \cdot P_{FCR} \quad (11)$$

If the capacity of the BESS is below this value, a schedule adjustment is triggered to recharge the battery on the intraday market. This value is valid for one direction, charge or discharge. The capacity has to be saved in both directions. In the case an integrated home is considered, the negative FCR can be transferred into the heat storage as shown in section 2.5. In this case, an integrated home with power-to-heat coupling and a 10 kWh BESS can provide up to 13.8 kW of FCR with the BESS.

Beside the battery capacity, the converter can be a limiting factor for participation in the FCR market. Considering the TSO regulations, 25 % of the converter capacity has to be available for recharging at all times. Therefore, a maximum of 8 kW from a 10 kW converter can be used for FCR.

If the charging power of the BESS is limited due to a high SOC, the heat can be transferred to the heating sector with the heating rod. The battery cell, which is used for parameterization of the BESS can be discharged with a current up to 2C. The 2C rate limit is set by the battery management system (BMS). Therefore, the discharge rate of the battery is not a limiting factor [57]. Only if the battery gets close to the discharge cut-off voltage, the discharging c-Rate is reduced. Table 2 provides an overview of the limiting factors of the integrated home for FCR.

The analysis leads to the conclusion that the battery converter and the grid inverter are the limiting factors for the FCR.

Component	Constraint	Size [kW]
Battery	SOC	13,8
	Charging power	— (limited by the power of the heating rod)
	Discharging power	20
Inverter	Rated power	8
Converter	Rated power	8

Table 2 Limiting factors of the available FCR power of the integrated home (10 kWh battery; 10 kW converter)

3.2.3 Advantages of the power-to-heat coupling in integrated homes participating in the frequency control reserve market

An advantage of integrated homes participating in the FCR market is that the negative FCR can be transferred into the heat storage as shown in section 2.5. The surplus FCR power can be transferred with a heating rod to the heating sector. Nevertheless, due to the high exegetic value of electricity, this is the last option. First of all the negative FCR power is used to reduce the grid consumption of the integrated home. If the energy consumption from the grid is zero the FCR power is stored in the BESS. Only if the BESS is fully charged $SOC = SOC_{max}$ the negative FCR is transferred into the heating sector via the heating rod. The heat pump is not used, because of the ramp up time of the heat pump. Additionally, the negative FCR power might not be sufficient to run the heat pump. Furthermore, FCR power might not be available for a sufficient time to guarantee the minimum runtime of the heat pump.

To be able to prequalify the integrated home in a virtual power plantfor the FCR market the heat storage capacity has to be sufficient to fulfil the 30-minute criterion. Therefore, the maximum capacity of the buffer and DHW storage is calculated. If the integrated home delivers 8 kW of FCR (size of converter), the storage capacity of the heating sector has to be 5.84 kWh at least. The minimum storage capacity of 5.84 kWh is calculated with equation (9). The volume of one storage is 300 l and the heat capacity of water is c = 4190 $\frac{J}{kg \cdot K}$. To fulfil the 30 min criterion the temperature spread in the storage has to be at least 14.3°C. An efficiency of the heating rod of 100% is assumed. The maximum output temperature of the heat pump is 55°C and the maximum valid temperature in the storage is 95°C [58]. Therefore, the minimum spread offered is 40°C. The storage capacity of the heating storage is sufficient for the FCR requirements.

3.2.4 Use of the degrees of freedom: over fulfilment and death band

Section 2.2 pointed out the degrees of freedom for BESS participating in the FCR market. These degrees of freedom can be used by the integrated home, to extract energy from the grid for free. If the integrated home should deliver negative FCR the degrees of freedom can be used. The integrated home can use the dead band as well as the over fulfilment.

Therefore, factors are implemented to use the potential of the degrees of freedom as shown in equation (12).

$$P_{PCR,total} = P_{PCR,min}(f) \cdot k_{over\ fulfilment}(f) \cdot k_{death\ band}(f) \quad (12)$$

These factors depend on the frequency and are shown in Table 3. A factor of 1.2 represents an over fulfilment of 20 %.

Degree of freedom	Frequency in Hz	Factor
$\mathrm{k_{death\ band}}$	$49.99 \leq f < 50$	0
	other	1
$\mathrm{k_{over\ fulfilment}}$	$49.8 \leq f < 50$	1
	$50 < f \leq 50.2$	1.2

Table 3 Usage of the degrees of freedom of a PV BESS

3.2.5 Battery operation in case of frequency control reserve

The BESS of an integrated home has a double use when participating in the FCR market. The capacity for the use as a home storage and the capacity for the FCR market are separated virtually. If the SOC band of the FCR is reached, the load of the household is not covered by the BESS. As soon as the SOC reaches a value above the FCR SOC band, e.g. due to a schedule adjustment, the load of the household would be directly covered by the BESS. This would lead to an oscillation. Therefore, a band is defined in which the SOC of the battery has to be charged by solar power in order to cover the load from the household. Figure 9 illustrates this band.

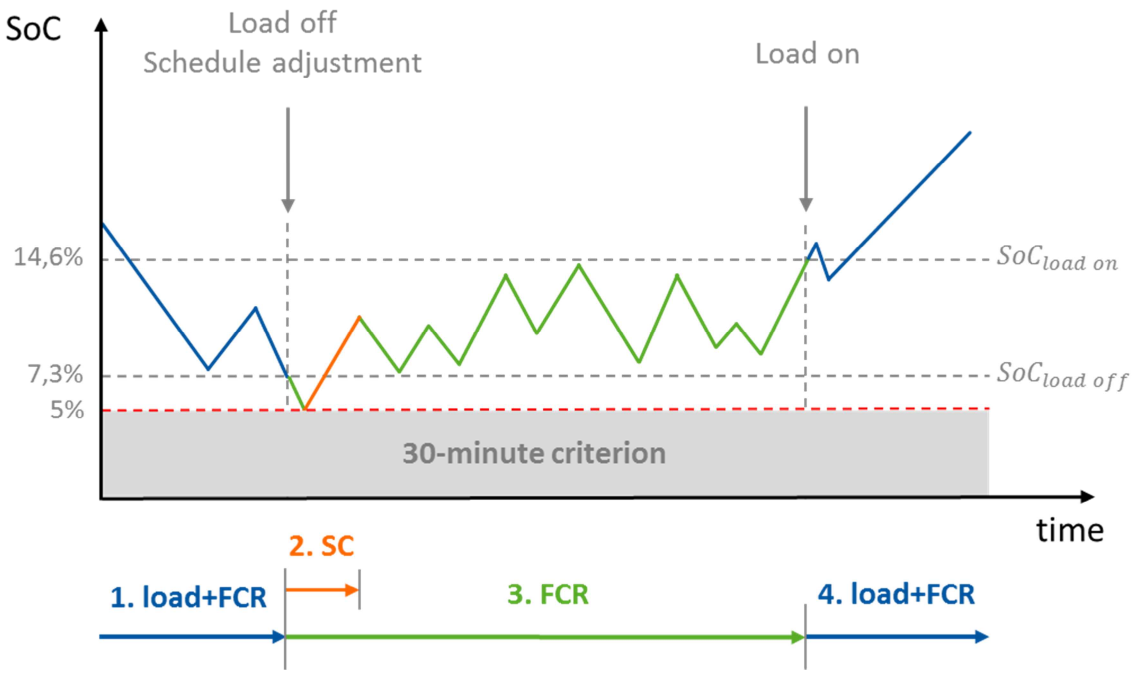

Figure 9: Battery operation of a PV BESS (1kW FCR; 10 kWh battery; 10 kW converter) in case of a FCR. If a schedule adjustment is necessary, the battery does not cover the load. Only when the SoC of the battery exceeds a defined boundary the battery covers the load.

3.2.6 Constant offer of frequency control reserve

In this work, two different kinds of FCR are examined: a constant and a variable offer of FCR power on the market. The constant FCR strategy offers constant FCR power over one year on the market. The SOC characteristic of the examined integrated home with 3 kW FCR is illustrated in Figure 10. The 30-minute criterion is minded.

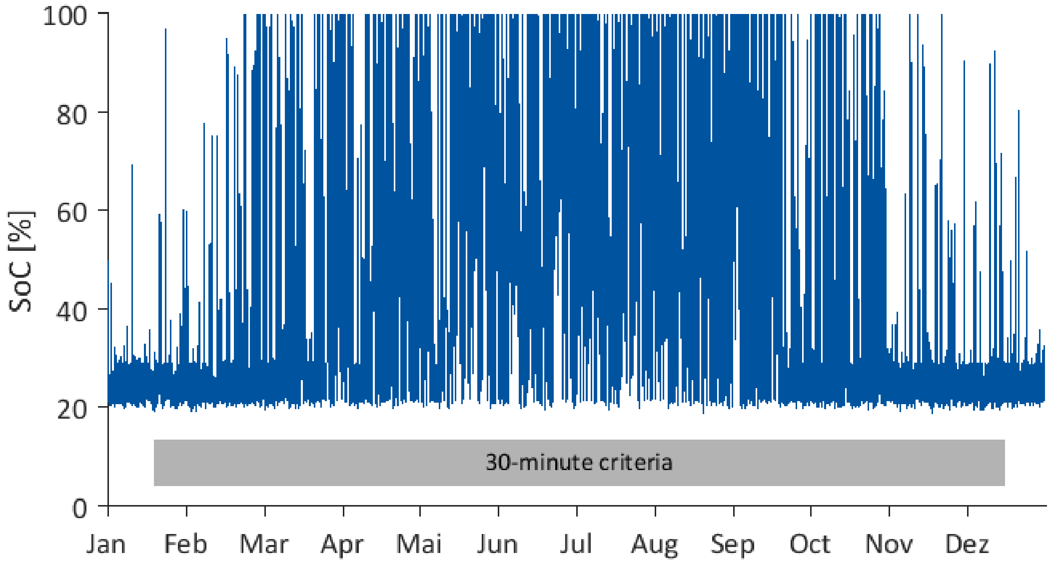

Figure 10: SOC of a PV-BESS with power-to-heat coupling and a 10 kWh BESS and a 10 kWp PV system offering a constant FCR power of 3 kW.

3.2.7 Variable offer of frequency control reserve

The 30-minute criterion limits the use of the battery for the home storage operation. In winter months the BESS is used less for home storage operation. Therefore, a higher share of FCR can be offered on the market, without major limitation of the home storage operation. Therefore, a variable offer of FCR, on the market is presented in this section. To determine the weekly offered FCR the assumption is made that waiver of 20 % of the energy stored in the BESS is acceptable.

Therefore, the SOC limit is chosen, which only reduces the energy throughput of the battery for the offered week by 20 % as shown in Figure 11.

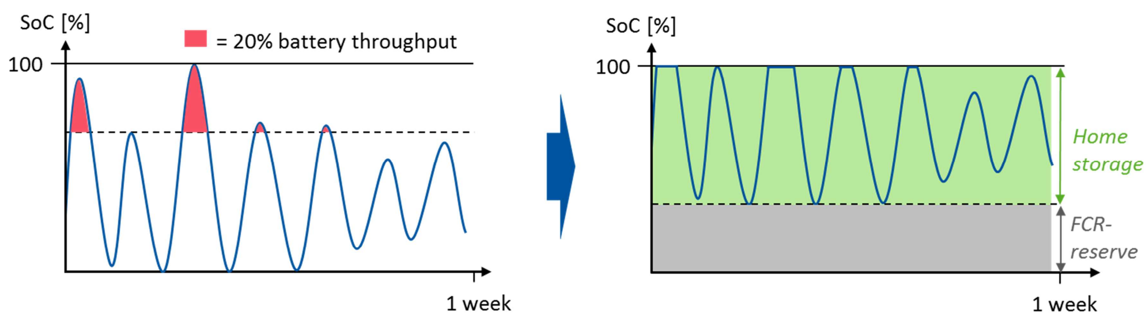

Figure 11: Calculation of the weekly offered FCR. Assumption that waiver of 20 % of the energy stored in the BESS is acceptable (Left). The SOC limit for this week is the SOC, which only reduces the energy throughput of the battery for the offered week by 20 % (right)

The 80 % energy boundary represents the SOC band for the home storage operation. The rest of the band can be used for FCR. With respect to the factor $a_{FCR} = 0.0726/\mathrm{kW}$ presented in section 3.2.2, the offered FCR can be calculated with equation (13).

$$P_{FCR,week} = SoC_{FCR,week}/(100\ \% \cdot a_{FCR}) \quad (13)$$

In winter months the battery is used less for home storage operation, therefore the offered FCR is higher in the winter month. The weekly offered FCR is depicted in Figure 12 with respect to the 8 kW limit of the converter. The determination of the weekly offered FCR requires forecast of the load and the PV feed-in. The influence of prognosis errors is not examinated in this work. The variable offer of FCR power leads to an average offer of $5.9\ \frac{\mathrm{kW}}{\mathrm{week}}$.

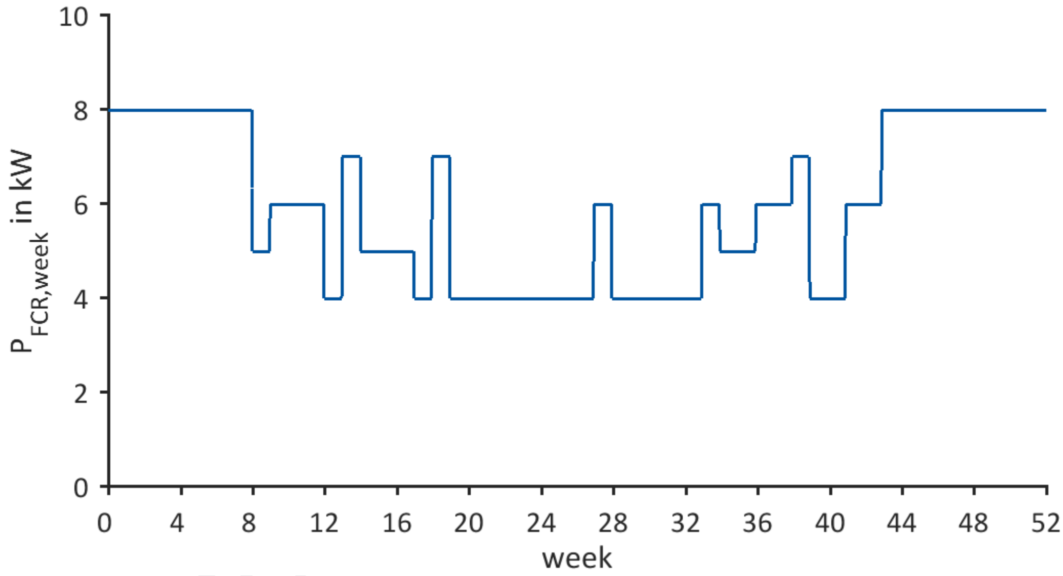

Figure 12: Resulting variable FCR offer of a PV BESS with power-to-heat coupling and a 10 kWh BESS and a 10 kWp PV system

3.3 Evaluation of the impact of the participation in the control reserve market

For evaluation of the impact of the participation in the control reserve market, the annuity is chosen. The evaluation based on the annuity is presented in [47] and [44]. The annuity is calculated by multiplying the present value with the annuity factor. The annuity factor incorporates the interest rate and the calculation period and can be calculated with equation (14).

$$f_A = ((1 + i_{calc})^{t_{calc}} \cdot i_{calc})/((1 + i_{calc})^{t_{calc}} - 1) \quad (14)$$

The net present value can be calculated with equation (15). The net present value (NPV) for the investment costs incorporates all costs over the system's lifetime including initial investment, cost of operation, maintenance costs and cost of capital. The present value covers the investment costs of the electric system including the cost for the battery as well as the cost for the three converters and the PV system. The investment costs of the heat system taking the costs for the storages, the heat pump and the cost for the pumps, electric installations and valves into account. The costs for reinvest and for savings because of residual values after the calculation are minded as well. Falling prices of the BESS due to scale effects in case of reinforcements are taking into account as shown in [59]. The net present value method is used and described in [60] as well.

$$Net\ present\ value_0 = \sum_{j=0}^{t_{calc}-1}((1+d)/((1+i_{calc})))^j \cdot C_j \quad (15)$$

The variable costs are calculated with the same approach and consist of the cost for the grid exchange, concerning the net present value of the electricity costs and savings due to the PV feed-in tariff. The changes of the electricity prices are evaluated by using an electricity price-increasing factor. Maintenance costs for the electricity sector as well as for the heating sector are considered as fix costs. The economic parameters for the calculation of the annuity are presented in Table 4 and Table 5. The annuity is calculated with equation (16).

$$\mathrm{Asum_{ges}} = present\ value_{\mathrm{I}}(\mathrm{i_{calc}}, \mathrm{d_I}) \cdot \mathrm{f_A} + present\ value_{\mathrm{V}}(\mathrm{i_{calc}}, \mathrm{d_V}) \cdot \mathrm{f_A} + \mathrm{F_t}(\mathrm{i_{calc}}) \quad (16)$$

$present\ value_{\mathrm{I}}$: present value of the investment costs
$present\ value_{\mathrm{V}}$: present value of the variable costs
$\mathrm{F_t}$: present value of the fix costs
i_{calc}: Interest rate
d: Discount rate

The Table 4 and Table 5 provide an overview on the input data of the model and the price assumption for the annuity calculation. Table 4 shows the economic parameters for the electricity sector and Table 5 for the heating sector.

Parameter	Value	Unit	Description
$\mathrm{t_{calc}}$	15	a	calculation period for invest assessment
$\mathrm{i_{calc}}$	1.3	%/a	interest rate
$\mathrm{c_{bat}}$	250	€/kWh	specific battery cost
$\mathrm{i_{bat}}$	7	%/a	annual battery cost degression
$\mathrm{c_{conv}}$	158	€/kW	specific converter cost of one converter, the model contains three converters
$\mathrm{L_{conv}}$	20	a	converter lifetime
$\mathrm{c_{PVgen}}$	1170	€/kWp	specific PV generator cost
$\mathrm{L_{PVgen}}$	20	a	converter lifetime
$\mathrm{c_{feed-in}}$	0.122	€/kWh	feed-in tariff (Sep. 2017)
$\mathrm{c_{electricity}}$	0.292	€/kWh	electricity costs (Sep. 2017)
$\mathrm{i_{electricity}}$	1.85	%/a	annual electricity price increase
$\mathrm{i_{maintenance}}$	1.5	%/a	annual maintenance cost relative to investment cost
c_{EPEX}	0.0367	€/kWh	average price EPEX 2017 [61]

Table 4: Input data for the annuity calculation electrical sector

Heating system

Parameter	Value	Unit	Description
$c_{heat\ pump}$	9130	€	specific costs heat pump
c_{buffer}	677	€	specific costs buffer storage
c_{DHW}	1064	€	specific costs DHW storage
$c_{pump\ DHW}$	150	€	costs DHW pump
$c_{pump\ heat}$	150	€	costs heat system supplying pump
$c_{heater\ rod,buffer}$	275	€	costs heater rod buffer storage
$c_{3\ way\ valve}$	300	€	costs 3 way valve
$c_{elec.\ installation}$	500	€	costs elec. installation [62]
$i_{maintenance\ ,HP}$	50	€/a	annual maintenance costs of the heat system
$L_{heat\ pump}$	20	a	heat pump lifetime [63]
$L_{heater\ rod}$	25	a	heater rod lifetime
$L_{storage}$	25	a	storage lifetime [63]
$L_{3\ way\ valve}$	20	a	3 way valve lifetime
$L_{elec.\ installation}$	20	a	elec. installation lifetime
L_{pump}	10	a	pump lifetime [63]

Table 5: Input data for annuity calculation heating sector

Cost for measurement and participation on the FCR market influence the economics of the integrated home. The cost for market participation rely on many factors, therefore a general statement cannot be made. Furthermore, the assumed costs depend on the current market situation. Future cost savings through progression in automation, novel measurement methods and centralized regulation are not taken into account. Additional costs for the market access and marketing of the FCR power are not investigated as well. Table 6 provides an overview of the range of costs for market participation. The costs are classified in investment cost (CAPEX) and operational cost (OPEX).

	Cost type	Costs in €
CAPEX	Installation of measurement device (control unit) • Steering software • Communication technology • Measurement technology	299 – 1000 € [64, 65]
OPEX	Current payments for measurement point • Operation of measurement point • Measurement service • Billing • Communication	325– 650 €/a [66]

Table 6: Cost for participation on the FCR market of a BESS operating in a virtual power plant.

A control unit for the FCR measurement point is offered by gridX for 299 € [65]. Caterva, the only company prequalified with a virtual power plant of PV-BESS to participate in the Central European FCR market estimates cost for a control unit of over 1000 € [64]. The investment cost can be apportioned over the lifetime.

The INEES research project estimates costs on automatic frequency restauration reserve (aFRR) participation of EV`s of 700 €/a per EV and estimates future costs of 60-250 €/a, due to changes in the measurement regulatory and the integration of smart meters [67].

A worst-case and a best-case scenario evaluation are made of the additional costs for market participation. The results are presented in Figure 19. The investment costs of 299 € are leading to annual costs of 16.85 €/a. The investment costs of 1000 € are leading to annual costs of 56.37 €/a. The operation costs in the worst-case scenario are set to 650 €/a [66]. For the best-case scenario the operation costs are set to 325 €/a, which are half of the costs in the worst-case scenario.

4 Results and Discussion

The following section presents the results from simulation and economic evaluation of the market participation of aggregated residential integrated home. Since there are many different relevant aspects to this evaluation, a discussion of the presented results is directly included in this section to increase readability and comprehensiveness.

The participation on the FCR market generates additional incomes for integrated homes. On the other hand, additional costs due to higher battery aging and lower self-consumption emerge. Section 4.1 investigates the influence on the battery aging. The influence on the self-consumption rate is examined in section 4.2. An economic evaluation of costs and revenues of the participation on the FCR market is analyzed in section 4.3. Section 4.4 presents an examination of the influence of the costs for participation on the FCR market. A comparison of all these costs with the possible incomes is presented.

4.1 Influence on the battery aging

To participate in the FCR market the 30-minute criterion has to be fulfilled as pointed out in section 2.1. This leads to an elevated average SOC of the battery and hence to an accelerated battery aging. The influence of the market participation on the average SOC of the BESS is depicted in Figure 13. The reserved capacity to satisfy the 30-minute criterion is also illustrated by the gray area. With a rising FCR power, the SOC capacity for the 30-minute criterion is elevated. Hence, the average SOC of the BESS is increased. In the case of a provision of 8 kW FCR, the capacity reserved is 58 % of the total battery capacity. This leads to an average SOC of 72.5 % and therefore to an increased battery aging [68]. The corresponding aging increase is illustrated in Figure 14.

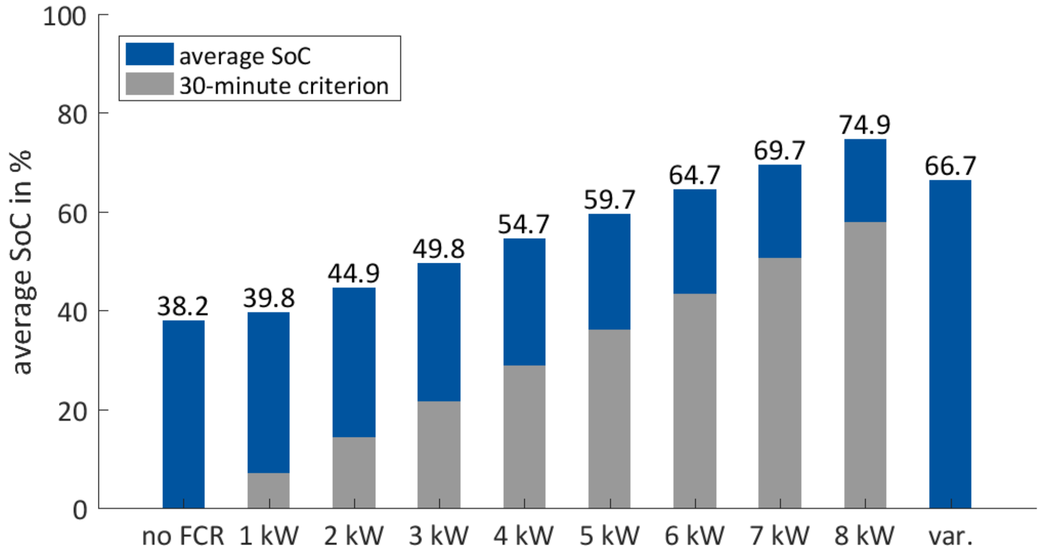

Figure 13: Average SOC in dependency of the FCR offer of a PV BESS with power-to-heat coupling with a 10 kWh BESS and a 10 kWp PV system.

An increased battery aging leads to higher costs of the BESS. The relative battery lifetime decrease is depicted in Figure 14. The result only applies for this specific battery cell. Due to the huge variety of different battery cells, a general statement cannot be made and has to be investigated for every cell individually.
For this battery cell, low rates of FCR power (1-5 kW) lead to a quite minor change of the battery aging. A FCR power of 6 kW reduces the BESS lifetime by around 5 %.

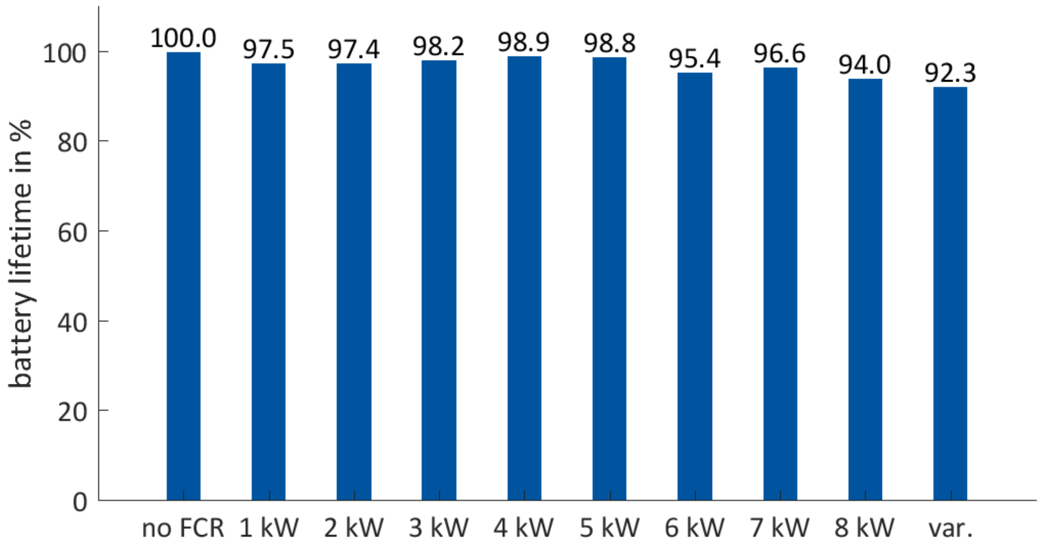

Figure 14: BESS lifetime in dependency on the FCR offer of a PV BESS with power-to-heat coupling with a 10 kWh BESS and a 10 kWp PV system.

For further investigation of the battery aging, the battery aging is divided into two parts, a calendric and a cycle aging. Figure 15 depicts the relative battery aging. An increase of the calendar aging is shown, due to the increased average SOC of the battery. A high average SOC leads to an increased calendric battery ageing [68].

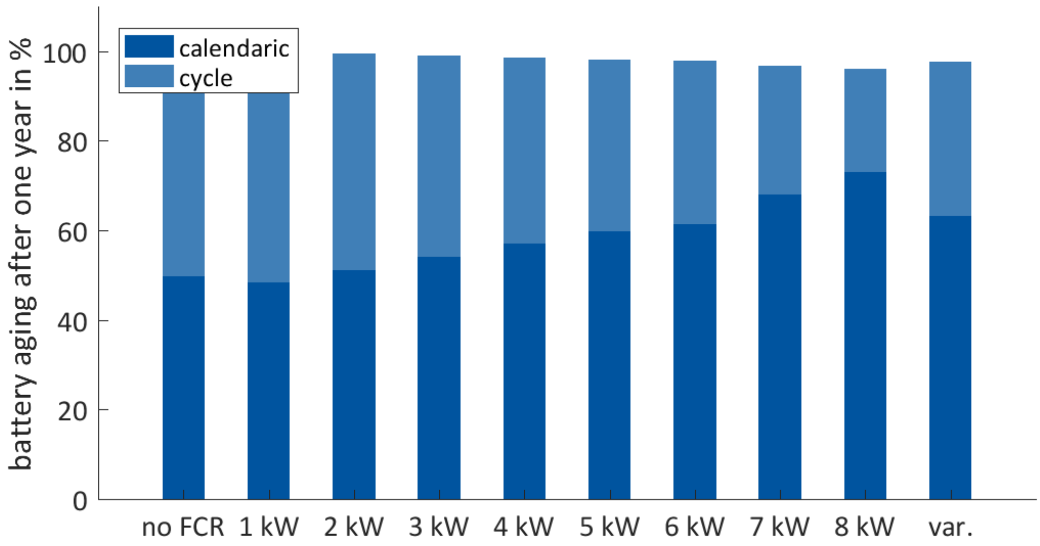

Figure 15: Calendar and cycle aging in dependency of the FCR offer of a PV BESS with power-to-heat coupling with a 10 kWh BESS and a 10 kWp PV system. The calendric aging is increasing, because the average SoC is elevated.

Besides the calendar aging, the cycle aging of the BESS is depicted in Figure 15 as well. In comparison to the calendar aging, the share of the cycle aging is reduced. The reason for the reduction is the reduced useable capacity for the home storage operation. The contrary effects of reduced cycle aging and the increased calendar aging have an equalizing effect. This is the explanation for the minor influence on the battery aging depicted in Figure 14.

4.2 Influence on the self-consumption rate

The participation on the FCR market leads to a limitation of the home storage operation, because capacity in the BESS is reserved for the FCR operation. The operation strategy of the BESS aims to maximize the self-consumption rate [47]. Therefore, the self-consumption rate is an indicator for the home storage operation and provides a measure for the amount of energy from the PV power plant that is used by the household. The self-consumption rate is defined as the sum of the direct self-consumption plus energy stored in the BESS divided by the energy produced from the PV power plant.

$$a_{SC} = (E_{direct\ SC} + E_{bat\ charge})/E_{PV} \quad (17)$$

Figure 16 depicts the self-consumption rate for different FCR offers. With an increasing FCR offer, the self-consumption rate is reduced. Therefore, the battery is used less for home storage operation. The self-consumption rate of the variable operation strategy is higher than that of an 8 kW constant FCR.

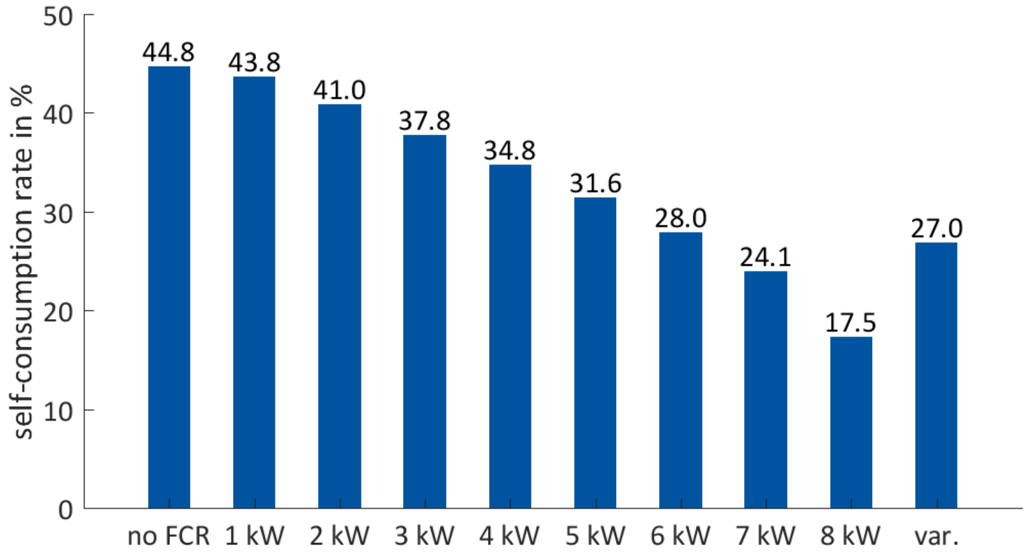

Figure 16: Self-consumption rate in dependency of the FCR offer of a PV BESS with power-to-heat coupling with a 10 kWh BESS and a 10 kWp PV system.

4.3 Economic evaluation

The economic evaluation is based on the method and the parameters presented in section 3.3. The assumption is made that the integrated home is participating in a virtual power plant on the FCR market. The virtual power plant is prequalified for the FCR participation. Therefore, additional costs are not taken into account. The influences of these costs are discussed in section 4.4. The cost for market participation varies in a wide range [64, 66, 69]. Hence, it is difficult to give a clear statement regarding these costs. This section investigates the additional revenues for BESS participating in the FCR market and the costs for reduced self-consumption rate and accelerated battery aging. Further savings due to additional energy gained from the utilization of the degrees of freedom are taken into account. The depicted results present the annuity of the integrated home. The annuities are the costs for electricity and heating of the integrated home. Lower annuities lead to lower costs. Therefore, integrated houses with lower annuity have higher economics. The annuities are depicted in Figure 17. The results emphasis that the offer of 1 kW FCR already lead to reduced annuity in comparison to an integrated home not participating in the FCR market. The integrated house offering variable FCR has the lowest annuity and therefore the highest economics. Costs for participation are neglected in this evaluation. The annuity of the integrated homes is compared to a house with fossil heating. This house uses grid consumption for electricity of 29.2 ct/kWh and fossil heating of 13 ct/kWh$_{th}$ [70].

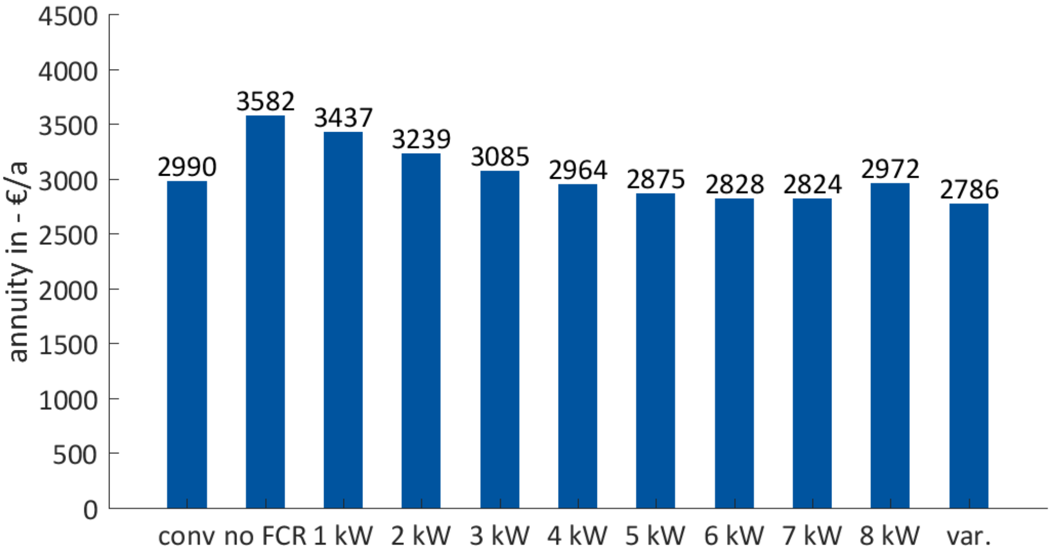

Figure 17: Annuity in dependency on the FCR offer of a PV BESS with power-to-heat coupling, a 10 kWh BESS and a 10 kWp PV system. A constant FCR revenue of $2.00\ €/(\mathrm{kW} \cdot \mathrm{week})$ is considered. Comparison to a conventional power generation (annual consumption: 4674 kWh_{el} with 29,2 ct/kWh and 12499 kWh_{th} with 13 ct/kWh [70])

The results presented in Figure 17 are based on constant FCR revenue of $2.00 \frac{€}{\mathrm{kW \cdot week}}$. A sensitivity analysis of the FCR prices is presented in Figure 18 on an integrated home offering a variable FCR power. The annuity incorporates the inflation rate. Therefore, annual decreases of five percent of the FCR costs lead to a FCR price of $0.62 \frac{€}{\mathrm{kW \cdot week}}$ in 20 years. This leads to an annual FCR remuneration of 752 €/a in the first year and an annual FCR remuneration of 233 €/a in 20 years. This is the explanation for the annuity increase of 6 %, if a 5 % decrease of the FCR price is estimated.

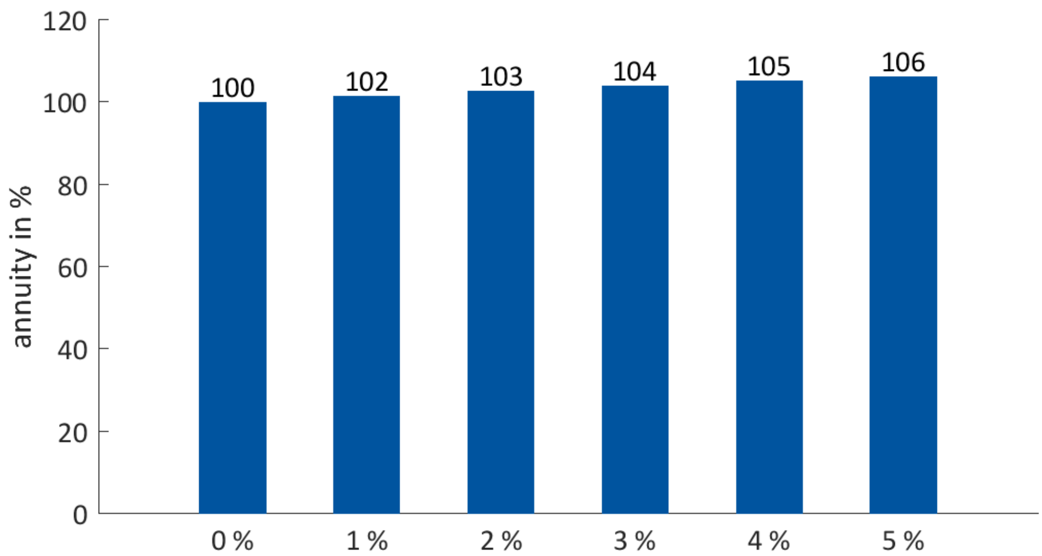

Figure 18: Sensitivity analysis of the FCR price offer by a PV BESS with power-to-heat coupling, a 10 kWh BESS and a 10 kWp PV system. A basic FCR price of of $2.00\ €/(\mathrm{kW} \cdot \mathrm{week})$ is considered. The integrated home offers a variable FCR power.

4.4 Influence of the costs for participation on the frequency control reserve market

This section analyses the influence of the measurement cost and operational cost for FCR market participation. The cost for market participation in the best and worst case is shown in Table 6, as well as the case if there are no additional costs for the market participation. The results in case of no additional cost for market participation are based on the annuities depicted in Figure 17.The annuities of the integrated home participating in the FCR market including costs for market participation are presented in Figure 19.

The results in Figure 19 emphasize, that the participation in the FCR market could be economically beneficial, if 3 kW or more are offered. In the worst-case scenario, a minimum offer of 6 kW FCR enhances the economics. Costs for market excess and changes in the market prices are not incorporated [22]. In the best-case scenario, annual savings up to 12.5 %/a are possible, with a variable FCR offer.

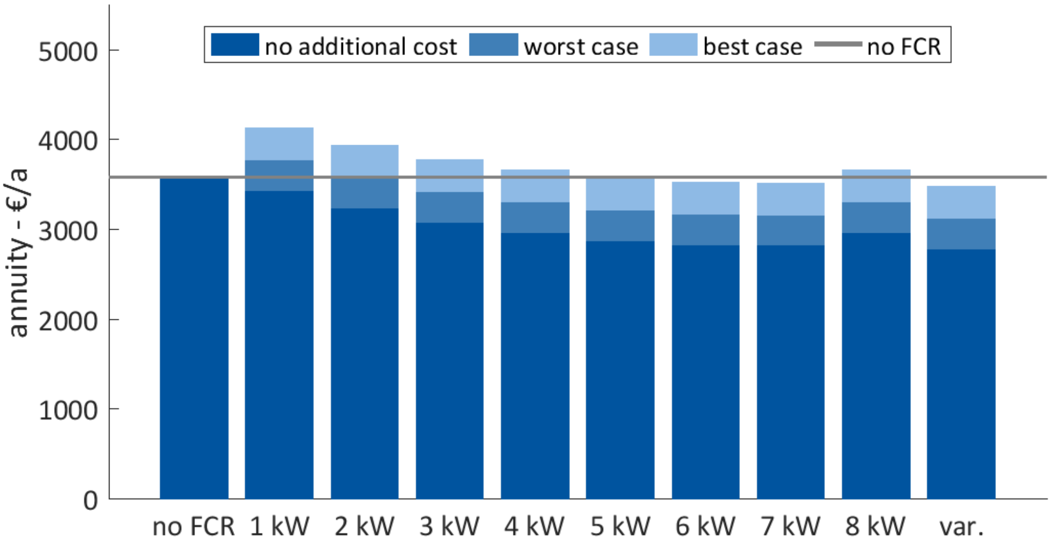

Figure 19: Annuity in dependency of the FCR offers of a PV BESS with power-to-heat coupling with a 10 kWh BESS and a 10 kWp PV system. A constant FCR revenue of 2.00 $€/(\mathrm{kW} \cdot \mathrm{week})$ is considered.

4.5 Sensitivity analysis with variable frequency control reserve offering

In section 3.2.7, a strategy to offer a variable amount of energy on the FCR market is presented. This strategy is used in section 4.1 to 4.4. For the investigated strategy the assumption is made that waiver of 20 % of the energy stored in the BESS is acceptable. A waiver of 20 % of the energy stored in the BESS leads to a remaining stored energy of 80 %. Figure 20 depicts the resulting annuity of the investigated integrated home, if the amount of waived energy is varied with a 5 % step size. The results lead to the conclusion that a waiver of 20 % of the energy stored in the BESS leads to the lowest annuity and therefore to the highest economic efficiency. Intelligent algorithms to calculate the FCR power offered on the market can lead to further reduction of the annuity of the integrated home. A reduction of the step size in the presented sensitivity analysis might further increase the economic efficiency.

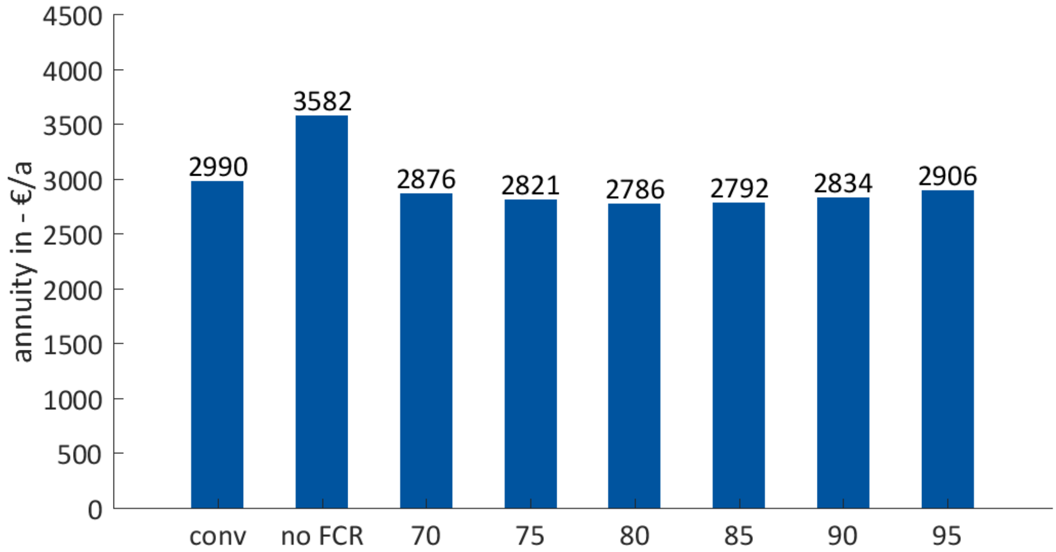

Figure 20: Annuity in of the variable FCR offers of a PV BESS with power-to-heat coupling, a 10 kWh BESS and a 10 kWp PV system. A constant FCR revenue of $2.00\ €/(\mathrm{kW} \cdot \mathrm{week})$ is considered. Different waivers of FCR are investigated. An energy waiver of 20 % leads to a stored energy of 80 %.

5 Conclusions

This paper presents an extension of the single-use operation of conventional residential storage systems to a dual-use operation of an integrated home with participation in the frequency control reserve market. The integrated home combines a photovoltaic battery energy storage system with a heat pump and thermal storages for power-to-heat coupling and can participate on the frequency control reserve market as part of a virtual power plant. To participate on the frequency control reserve market, the 30-minute criterion has to be fulfilled. The 30-minute criterion ensures that the battery storage system can provide the maximum frequency control reserve power for at least 30 minutes. Thermal storages can also be used to absorb the negative control reserve power. The publication at hand points out the advantages in comparison to photovoltaic battery energy storage systems without power-to-heat coupling.

The influence on the economics of the integrated home is investigated. Therefore, load and radiation profiles based on real data measurements are used as input for the simulations. The provision of frequency control reserve generates additional incomes for the integrated home. Due to over-fulfillment, free-of-charge energy can be obtained. On the other hand, the provision of energy in the battery storage system for frequency control reserve leads to an elevated average state of charge of the battery system. The elevated state of charge leads to accelerated battery aging, mainly driven by increased calendar aging. Furthermore, the additional use of the integrated home on the frequency control reserve market reduces the self-consumption rate from the photovoltaic power plant. The economic assessment shows that the additional costs for the increased battery aging and the reduced self-consumption rate are compensated by the income from the FCR market participation. The dual-use operation of an integrated home that participates in the frequency control reserve market can increase the profitability of a residential storage system. Thereby, integrated homes profit from the additional flexibility provided by the thermal storages. In conclusion, this paper helps manufacturers of residential battery storage systems and operators of virtual power plants to understand the influence of additional frequency control reserve market participation on residential battery storage systems. Advantages of integrated homes with thermal storages are pointed out and the limited influence on battery aging, operation and self-consumption rate are shown.

Results show that under consideration of steady revenues and low costs for market participation, a provision of at least three kilowatts of reserve power could be economical. Nevertheless, prices for frequency control reserve provision were falling in the recent years. Costs for the virtual power plant operation and market access are not transparent, as well as charges for aggregators. Experts estimate an average income of 100,000 €/(a·MW). Further additional costs for market participation are estimated at 25 % of the income for grid scale storages. These costs might be higher for small storages operating in a virtual power plant. The aggregation of small photovoltaic battery energy storage systems for market participation is challenging, since a complex measurement procedure has to be installed. Finally yet importantly, in Germany additional charges (e.g. Renewable Energies Act levy (EEG-Umlage), grid utilization charges (Netznutzungsentgelt), interruptible loads levy (Umlage für abschaltbare Lasten)) are added for electricity from frequency control reserve power that is converted to heat. On the other hand, a reduction of the transaction costs is possible if not every single integrated home is monitored. Additionally, further combination with the intraday market could lead to additional incomes.

Seasonal variation of feed-in from photovoltaics is considered by an advanced bidding strategy for variable provision of frequency control reserve power. The advanced operation strategy chooses to bid on the frequency control reserve market in dependency of the solar energy production. The results show that such a strategy can further increase the economic efficiency of integrated homes providing frequency control reserve. The incorporation of weather prognosis could further enhance the incomes in case of variable offering of frequency control reserve power. The flexibilisation of the frequency control reserve market and the introduction of the 15-minute criterion lead to further incentives for storage systems to participate in this market.

6 Acknowledgment

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Providing frequency control reserve with photovoltaic battery energy storage systems and power-to-heat coupling

Highlights:

- Investigation integrated home: photovoltaic battery storage and power-heat coupling
- Enhanced economics of integrated homes by participating on frequency reserve market
- Additional flexibility to absorb the negative control reserve in the heating sector
- Provision of at least 3 kW frequency control reserve could be economical
- Season dependent provision of frequency control reserve further enhances economics

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: