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Price development and bidding strategies for battery energy storage systems on the primary control reserve market

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Abstract

Decreasing prices on the German primary control reserve (PCR) market lead to an uncertain economic situation for battery energy storage systems (BESS) providing PCR. In a simulation-based approach, which takes into consideration application-specific aging, an economic assessment of a 1.5 MWh BESS providing PCR is conducted. Different bidding strategies for PCR auctions have been developed and their impact on revenues and battery aging has been investigated. Furthermore, following an option value approach, we analyzed how different PCR price paths and the time of investment affect the economic feasibility of BESS providing PCR.

The results show that the choice of strategies developed in this paper do not have a substantial influence on revenues and battery aging. However, the development of PCR market prices and battery system costs is crucial for the economic feasibility of BESS providing PCR. Investments come with a high risk due to the volatility of PCR market prices and the uncertainty of future battery system prices.

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Keywords: Battery energy storage system; primary control reserve; economic assessment

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1. Introduction

Stabilizing the electricity grid is a major challenge for system operators, particularly with a growing share of intermittent renewable energy sources feeding into the grid. Since the electricity grid is not capable of storing energy, control reserve is required to balance feed-in and consumption. Primary control reserve (PCR) is the product with the fastest response time and the shortest deployment period in the interconnected grid of the European Network of Transmission System Operators (ENTSO-E) Regional Group Continental Europe. PCR is tendered by the responsible transmission system operator and traded on separate markets with specific regulatory frameworks.

This paper focuses on the German PCR market, which has undergone a dynamic development in recent years. This includes the integration of neighboring countries and an increasing share of stationary battery energy storage systems (BESS) providing PCR. In 2016, a rapid drop in PCR capacity prices could be observed. This development raises the question whether providing PCR is a sustainable business model for BESS operators.

We aim to investigate the economic feasibility of BESS providing PCR in the given framework, focusing on bidding strategies of BESS operators in PCR auctions and on future price paths for PCR capacity prices. In order to calculate revenues and losses, a model has been developed to simulate BESS operation and aging. Different bidding strategies and price paths are implemented to analyze their respective impact on economic feasibility.

Nomenclature

BESS	battery energy storage system
CAP_{min}	power plant minimum load (MW)
CAP_{PCR}	amount of PCR capacity provided (MW)
C_{BESS}	battery capacity (MWh)
c_{var}	variable costs (€/MWh)
E	energy (MWh)
PCR	primary control reserve
p_{DA}	price on the day-ahead market (€/MWh)
p^{FC}_{max}	maximum forecast PCR price (€/MW)
p^{FC}_{min}	minimum forecast PCR price (€/MW)
p^{FC}_{wa}	weighted average of forecast PCR prices (€/MW)
p_{PCR}	price on the primary control reserve market (€/MW)
$p_{PCR,0}$	price on the primary control reserve market in the base year (€/MW)
$p_{PCR,s}$	price on the primary control reserve market at saturation level (€/MW)
SoC	state of charge (%)
ΔE_{DU}	energy exchanged due to deadband utilization (MWh)
ΔE_{OF}	energy exchanged due to overfulfillment (MWh)
ΔE_{PCR}	energy exchanged due to PCR provision (MWh)
ΔE_{SC}	energy exchanged due to self-consumption (MWh)
ΔE_{ST}	energy exchanged due to schedule transactions (MWh)
λ	exponential decay constant (-)
η_{ch}	charging efficiency (-)
η_{dis}	discharging efficiency (-)

1.1. Literature review

Providing PCR has been found to be a high-value application field for stationary BESS owners [1]. Furthermore, using BESS instead of conventional power plants is a promising option to reduce environmental impacts of PCR provision [2]. In the literature, different aspects of this subject are investigated. A number of publications deal with operation strategies for charge level control of stationary BESS providing PCR and their impacts on energy throughput and charge levels [3-6].

Further papers discuss battery aging and economic aspects of PCR provision by battery systems. Hollinger et al. compare cost structures of BESS and conventional power plants [7]. Based on a simulation model, Fleer et al. evaluate battery aging and the economic feasibility of a BESS providing PCR in a case study for Germany [8]. Świerczynski et al. investigate performance degradation of lithium-ion cells and economic feasibility of BESS providing PCR on the Danish electricity market [9, 10]. The impact of a market entry of large numbers of BESS in the PCR market is discussed by [11] and [12]. Steber et al. investigate the possibility of providing PCR using distributed household photovoltaic BESS [13].

1.2. Development of the German PCR market

The German market for balancing power is divided into three sections, of which PCR is the product with the highest requirements in terms of reaction times and accuracy of regulation. The other two products traded are secondary control reserve and minute reserve. BESS work well for PCR provision as they offer short response times, precise controllability, high efficiencies and can be dimensioned flexibly. The regulatory framework of the market including prequalification requirements for technical units providing PCR is described in [14-18]. Table 1 summarizes the product characteristics of PCR in Germany.

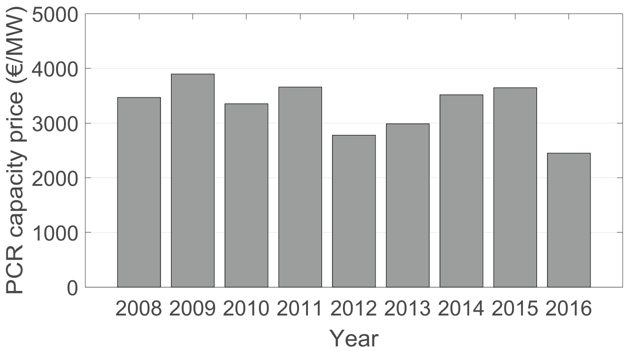

Fig. 1. Annual average PCR capacity prices 2008-2016

Table 1. Product characteristics of primary control reserve in Germany (joint market area) [19]

Primary control reserve (PCR)	
Tender period	one week
Minimum bid size	1 MW
Increment of bid size	1 MW
Call for tender	capacity price [€/MW] merit-order
Remuneration	pay-as-bid (capacity price)
Market size	approx. 1,250 MW (joint tender of German, Dutch, Belgian, Swiss, French and Austrian TSOs)

In recent years, the German PCR market has developed from a bilateral oligopolistic market with five providers in 2007 to a more competitive market with 22 providers in 2016. As of January 2017, 603 MW of PCR are tendered in the German control area. TSOs from the Netherlands, Belgium, Switzerland, France and Austria also use the German auction platform to tender parts of their PCR demand, which results in an effectively bigger market size (see Table 1) [19].

Fig. 1 illustrates the development of the average PCR capacity price from 2008 to 2016. From 2008 till 2011 prices fluctuated on a relatively high level between approx. 3,300 and 3,900 €/MW. In 2012, the average price dropped for the first time by 24 % to 2,779 €/MW. Prices recovered to a value of 3,464 €/MW in 2015. In 2016, the second price drop occurred, this time by 33 % to 2,451 €/MW, which is the lowest value since 2008.

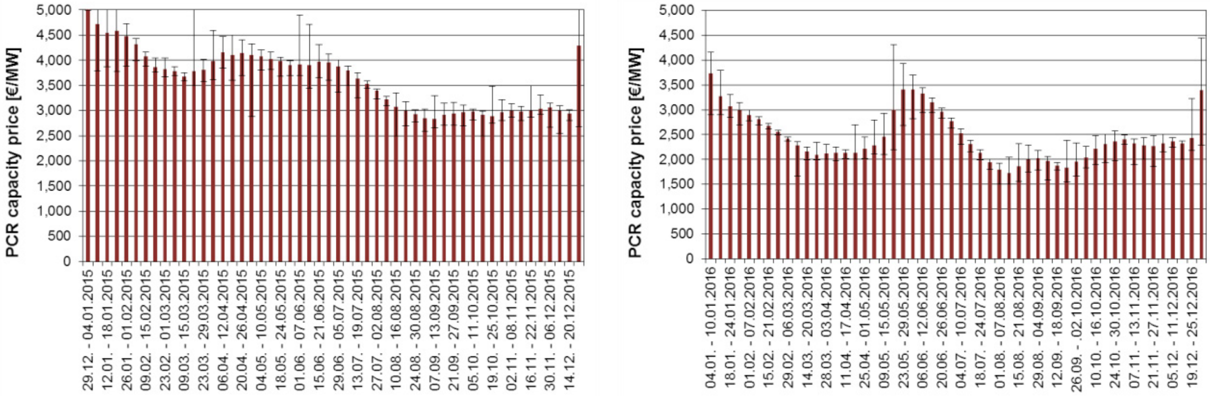

Fig. 2. Weekly average PCR capacity prices in 2015 (left) and 2016 (right) with maximum and minimum accepted bids in the respective weeks

Fig. 2 shows the weekly average PCR capacity prices in the course of the years 2015 and 2016. Throughout 2015, prices were on a higher level compared to 2016. The development of prices throughout the year is similar in 2015 and 2016. Prices decrease from the beginning of the year till March/April and then increase again. From June till August, prices drop and remain on a relatively low level until the second last week of the year. The main differences between both years are the overall price level, the lower weekly spreads, and the slopes between high-price and low-price phases, which are steeper in 2016.

The entry of stationary battery systems is another important development on the German PCR market. In 2012, the first prototypes for PCR provision started operation. Two years later, the first commercial 5 MW/5 MWh system entered the market [20]. In 2017, 187 MW of PCR will be provided by BESS (market share approx. 31 %) if all announced projects are realized and accepted in the bidding process (Fig. 3).

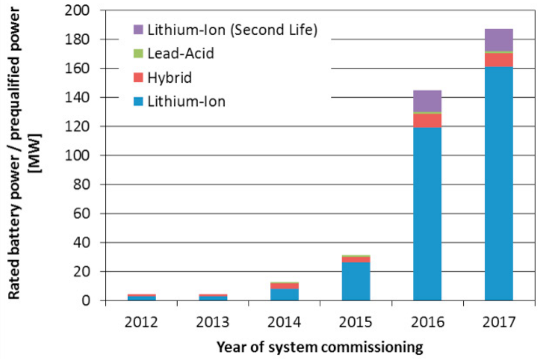

Fig. 3. BESS providing PCR in Germany

1.3. Research objective

Currently, it is unclear how the increasing number of market participants and the entry of BESS will influence the PCR price and vice versa. The economic feasibility of BESS providing PCR, however, strongly depends on the revenues which can be achieved on the market. In this context, this paper investigates how these revenues are influenced by the market development. Firstly, we analyze how different bidding strategies affect revenues and battery lifetime under the current market framework. Secondly, we look at the long-term development of the PCR market and investigate the impact of different price paths on the economic feasibility of BESS providing PCR

2. Methodology

The investigation of the impact of different bidding strategies on revenues is based on simulations of BESS operation. The BESS model used in this study simulates PCR provision, charge level management and battery aging.

Three types of bidding strategies have been developed based on PCR price forecasting and risk-aversion of the respective bidder and are analyzed using the BESS operation simulation model.

For the analysis of the impact of PCR price development on the economic feasibility of BESS providing PCR, distinct price paths for the coming years have been developed and are compared considering different years of system commissioning and different BESS lifetime expectancies.

2.1. Simulation of BESS operation

In order to assess the economic feasibility of the distinct operation strategies, a PCR simulation model has been developed. The simulation is time-discrete with a temporal resolution of one second. The model is based on a grid frequency time series and calculates the state of charge (SoC) of the BESS for every time step. Furthermore, measures for charge level management are simulated. These include deadband utilization, overfulfillment and schedule transactions. The model and the three measures are described in detail in [6] and [8].

The general approach is to calculate the grid-side power demand based on the grid frequency time series and the SoC based on an energy balance for every time step The energy balance takes into account the current amount of energy stored in the BESS (E), the amount of energy charged or discharged due to primary control provision (ΔE_{PCR}), the additional charge or discharge energy resulting from the distinct measures for charge level management (ΔE_{OF} for overfulfillment, ΔE_{DU} for deadband utilization and ΔE_{ST} for schedule transaction) and the self-consumption of the BESS (ΔE_{SC}). If energy is charged or discharged from/to the grid, the respective charging/discharging efficiency η_{ch}/η_{dis} needs to be considered.

$$E(t) = \begin{cases} E(t-1) + \eta_{ch}\left(\Delta E_{PCR}(t) + \Delta E_{OF}(t) + \Delta E_{DU}(t) + \Delta E_{ST}(t)\right) - \Delta E_{SC} \\ E(t-1) + \dfrac{1}{\eta_{dis}}\left(\Delta E_{PCR}(t) + \Delta E_{OF}(t) + \Delta E_{DU}(t) + \Delta E_{ST}(t)\right) - \Delta E_{SC} \end{cases} \tag{1}$$

The SoC is calculated by scaling the amount of energy stored in the BESS to the current capacity C_{BESS}.

$$SoC(t) = \frac{E(t)}{C_{BESS}(t)} \tag{2}$$

Depending on the current SoC, the model decides which measure for charge level management is used. Overfulfilment and deadband utilization are used to decelerate discharging and enhance charging when the SoC falls below 50 % and to decelerate charging and enhance discharging when the SoC exceeds 50 %. Schedule transactions are applied when the SoC falls below 35 % (charging process) or exceeds 65 % (discharging process). The power-to-capacity ratio of 1:1.5 and the SoC limits for schedule transctions have been chosen to comply with the so-called 30 minutes criterion, which has been established by the TSOs. It mandates batteries to be able to provide PCR at full power at any time for at least 30 minutes. The aging model is part of the operation simulation module. It simulates capacity fading of the BESS due to electrochemical degradation processes. The simulation is stops when a predefined end-of-life criterion (here 80 % of the nominal capacity, C_{nom}) is reached.

The net present value (NPV) approach is chosen to evaluate the economic feasibility of the BESS. In each of the four price scenarios, the NPV of the BESS is calculated as a function of the year of commissioning and the lifetime of the BESS. 2017 is chosen as the base year for the NPV calculations. The investment will be profitable if the NPV is positive at the BESS's end of life. The BESS considered in these calculations is assumed to offer 1 MW of PCR with a nominal capacity of 1.5 MWh. The system has been designed with an actual power rating of 1.8 MW as it has to be able to cope with simultaneous occurrence of a maximum PCR retrieval and a schedule transaction with a power rating of 0.8 MW.

The assumptions for the technical and economic parameters in the simulations are listed in Table 2.

Table 2. Technical and economic parameters applied in the simulations

Parameter	Value
prequalified power rating for PCR supply	1 MW_{PQ}
rated power	1.8 MW
nominal capacity at start	1.5 MWh
charging efficiency	95 %
discharging efficiency	95 %
self-consumption	13.86 kW per MW_{PQ} [2]
SoC set point for overfulfillment and deadband utilization	50 %
upper SoC limit for schedule transactions	65 %
lower SoC limit for schedule transactions	35 %
contract duration for schedule transactions	15 minutes
power rating and energy exchange per schedule transaction	0.8 MW / 0.2 MWh
end-of-life (EoL) criterion	80 % of C_{nom}
maintenance cost	2 % of investment per year
operating cost (excluding maintenance)	4,000 €/year
discount rate	5 % per year

2.2. Modeling battery aging

Battery lifetime analysis is a crucial aspect of the economic assessment of a BESS. Fading of usable capacity over the operation period reduces the operational window of a system and, in the case of PCR, may lead to a loss of prequalification if requirements cannot be met anymore. To incorporate the diminishing storage capacity into the economical assessment, a battery aging model is used. This model takes into account both cyclic and calendar aging. It consists of two separate functions: The first describes the loss of available battery capacity due to cyclic stress at different depths of discharge (DoD), the second represents calendar aging over time at different SoCs. These functions have been derived from a detailed battery model, consisting of a thermo-electrical model and an aging model [21]. The same approach was used by [22].

The method for cyclic aging is based on stress and failure (S-N) curves, while modeling of calendar aging uses Arrhenius' law to incorporate temperature dependencies of aging mechanisms, e.g. through ohmic losses. The effect of the SoC on calendar lifetime, together with all other relevant aspects of parameterization of the aging model, has been determined through accelerated aging tests on a large scale test matrix of Saft VL45E battery cells. The simplified approach is not able to accurately represent the superposition of both aging effects simultaneously; however, it significantly improves the in-situ determination of capacity fading through battery operation during simulation and the ensuing profitability analyses.

2.3. Implementation of bidding strategies

A fundamental forecast model for PCR prices has been developed. Based on price expectations, calculated with this model, bidding strategies for a BESS on the PCR market have been devised. Input parameters for the PCR price forecast model include the PCR prices of the drawn bids in the previous tender, the technology portfolio of each prequalified supplier of PCR in Germany and the historic prices on the Day-Ahead (DA) market for every week. The data for PCR prices (p_{PCR}) and DA prices (p_{DA}) can be found in [19] and [23]. All prequalified PCR members are listed on the German PCR tendering platform [19]. Information on all conventional power plants in Germany is published on a regular basis [24]. The conventional power plants are parameterized according to [25]. Power plant data are estimated using a linear interpolation between the mean values of the years 2013 and 2023 [25].

Opportunity costs are considered using the approach described in [26] to forecast PCR prices. In this approach, all power plant operators are assumed to maximize their revenues by choosing between the PCR and the DA market to offer the electricity generated in their plant. p_{PCR} [€/MW] for each MW of PCR power CAP_{PCR} is adjusted to the expected revenues or costs on the DA market for the upcoming week, in which PCR is supposed to be offered. Assuming constant variable costs c_{var} and neglecting start-up costs and revision times of power plants, it has to be distinguished between two possible situations on the DA market. The price on the DA market p_{DA} in a given hour is either higher than the variable costs c_{var}, which means that every additional megawatt of electricity sold on the DA market generates revenues $p_{DA} - c_{var}$, or c_{var} is higher than p_{DA}. This means that the minimal technical load CAP_{min}, which is required to operate a power plant and therefore to supply PCR, causes costs $c_{var} - p_{DA}$. Therefore, the minimum PCR price for every power plant and every week must be higher than or equal to the sum of the two mentioned scenarios over all hours of the respective week.

$$p_{PCR} = \sum_{t=1}^{t=168} \begin{cases} p_{DA,t} - c_{\text{var}} & ,if \ \ c_{\text{var}} \le p_{DA,t} \\ \left(c_{\text{var}} - p_{DA,t}\right) \cdot \dfrac{CAP_{\min} + CAP_{PCR}}{CAP_{PCR}} & ,if \ \ c_{\text{var}} > p_{DA,t} \end{cases} \tag{3}$$

We found that the forecast results were considerably more accurate when taking into account the marginal PCR price of the previous week. Therefore, the forecast model weights historic PCR prices with a factor of two and PCR prices calculated by equation (3) with a factor of one. The resulting price is used as bidding price for the forecast model. The bidding prices of all generation units are then brought into a merit-order until the required control reserve demand is satisfied. This merit-order is used to determine the maximum, minimum and CAP_{PCR} -weighted average PCR price (p^{FC}_{max}, p^{FC}_{wa}, p^{FC}_{min}) as forecast for each week.

Three types of bidders are introduced: a risk-averse bidder with strategy A, a risk-neutral bidder with strategy B, and a risk-loving bidder with strategy C (Table 3). These strategies are applied to the historic values of the years 2015 and 2016. The correlation of forecast and corresponding historic prices for maximum, minimum and weighted average are $R^2_{max} = 0.74$, $R^2_{min} = 0.88$ and $R^2_{wa} = 0.92$. Since p^{FC}_{max} and p^{FC}_{min} show an inferior fit to historic PCR prices, the bids for the three strategies are defined according to p^{FC}_{wa}. The risk-neutral strategy B is defined by the values of p^{FC}_{wa}. The risk-averse strategy A and the risk-loving strategy C are defined as $p^{FC}_{wa} \pm 5$ % respectively.

Table 3. Bidding strategies and corresponding forecast values

Strategy	Corresponding value of forecast simulation
Strategy A	$p^{FC}_{wa} \cdot 95\%$
Strategy B	p^{FC}_{wa}
Strategy C	$p^{FC}_{wa} \cdot 105\%$

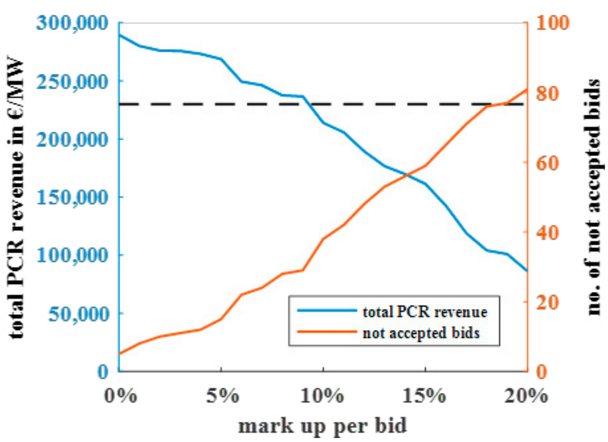

Fig. 4. Relation of total revenue and number of not accepted bids for mark-up on Strategy B for 2015/2016

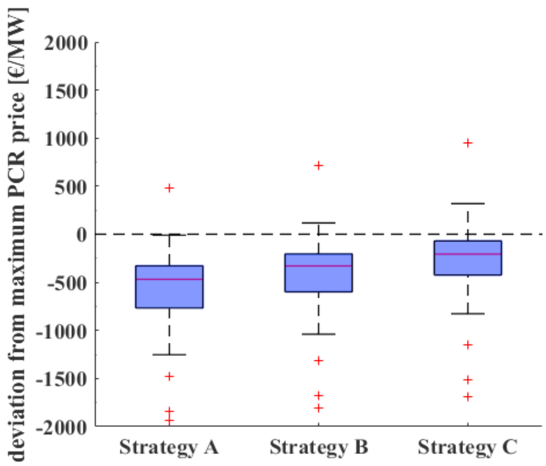

Fig. 5. Absolute deviation of each strategy's bid from the maximum PCR price of the respective week

Fig. 4 illustrates the effect of a positive price mark up on the total revenue of Strategy B for the years 2015 and 2016. It can be seen that a rising mark-up comes along with an increasing number of declined bids. This leads to a decrease in revenues from the PCR market. The dashed reference line shows the revenue that could be obtained following P^{FC}_{max}. A mark-up of 5 % is chosen because it seems to be a good trade-off between revenue and number of not accepted bids.

The absolute deviations of the strategic bidding to the historic maximum PCR prices are illustrated in Fig. 5. The red line marks the median, the blue boxes describe 50 % of the outcome of each strategy. The remaining data is shown by the whiskers. The view outliers are marked with a red cross. Strategy A overestimates prices once, strategy B four times, and strategy C overestimates prices 15 times within the 105 considered weeks. An overestimation leads to a rejected offer, so that the BESS will not provide PCR in the respective week and, thus, will not generate any revenues. On the other hand, an underestimation of the maximum possible price should be as small as possible to increase the revenue stream.

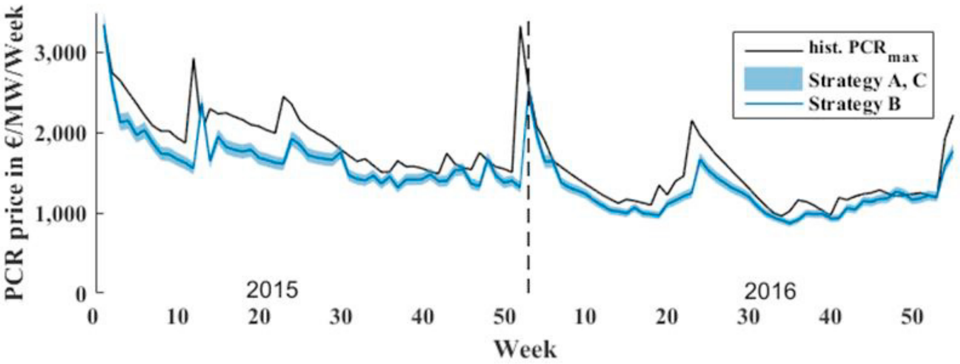

Fig. 6. Price curves of historic PCR and strategies A, B, C

The curves for the historic marginal PCR price as well as for the three strategies are depicted in Fig. 6. The blue curve displays strategy B, the lower and upper bounds of the light blue area display strategies A and C. The three strategies are considered in the economic simulation to calculate the associated lifetime expectancy.

2.4. Price paths

In order to assess the influence of the PCR price development in the coming years on the economic feasibility, four different price paths have been outlined. In each of these scenarios, a distinct development of the annual average PCR capacity price has been assumed. All four paths start in the year 2015 at a level of 3,500 €/MW per week, which roughly corresponds to the actual PCR price of 3,646 €/MW per week in 2015. The first price path assumes a price jump from 3,500 €/MW to 2,500 €/MW per week, which roughly corresponds to the 2016 average PCR capacity price. From 2016 on, the PCR capacity price is assumed to remain constant on this level. Two price paths model a decrease of PCR capacity prices from 3,500 €/MW to 1,000 €/MW per week, which has been found to be a reasonable assumption for long-term PCR prices [27, 28]. The first of these two paths assumes a linear decrease with a slope of 500 € per year, the second expects an exponential decrease of the form

$$p_{PCR}(t) = p_{PCR,s} + \left(p_{PCR,0} - p_{PCR,s}\right) \cdot e^{-\lambda t} \tag{4}$$

where t is the time in years (t = 0 representing the base year 2015), p the average PCR capacity price in the respective year, p_s the saturation price, p_0 the average PCR price in the base year, and λ the exponential decay constant. The fourth price path also assumes an exponential decrease of PCR prices as described by equation (4). The exponential-decrease paths differ regarding their saturation prices and their decay constants. Fig. 7 provides an overview of the four different price paths.

The investment for the BESS depends on the year of system commissioning since battery system prices are currently decreasing fast. Fig. 8 presents the price projection for the BESS investigated in this study. The system price is composed of a capacity-specific and a power-specific share. Capacity-specific prices for lithium-ion batteries and prices for power electronics are taken from [8]. Additional equipment like transformers (10 kV), contactors, fuses, control systems and air conditioning is taken into account with a lump sum of 100 €/kW.

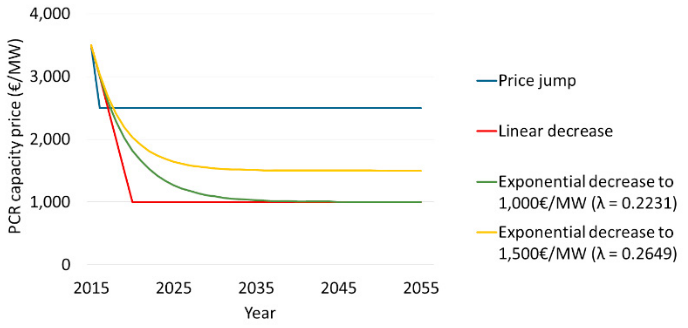

Fig. 7. Price paths for the PCR capacity price considered in the economic assessment

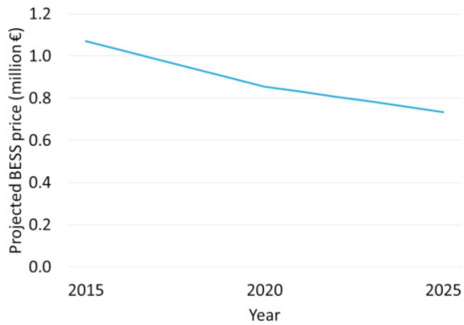

Fig. 8. Price projection for a 1 MW / 1.5 MWh BESS (actual power rating: 1.8 MW)

Furthermore, for the linear-decrease scenario, this approach is reversed. Originating from a system with a lifetime of 26 years, linearly decreasing price paths with their respective saturation values, for which the considered system reaches its break-even (i.e. reaches a positive NPV at the end of its lifetime), are calculated.

3. Results and discussion

In this section, the results of the impact analysis of the different bidding strategies and the price scenario analysis are presented. All results presented in this section are based on the 1 MW/1.5 MWh BESS described in section 2.1.

3.1. Impact of bidding strategies on revenues and aging

In order to investigate the impact of the three different bidding strategies, attainable revenues for the respective bidder types have been calculated and aging simulations have been carried out.

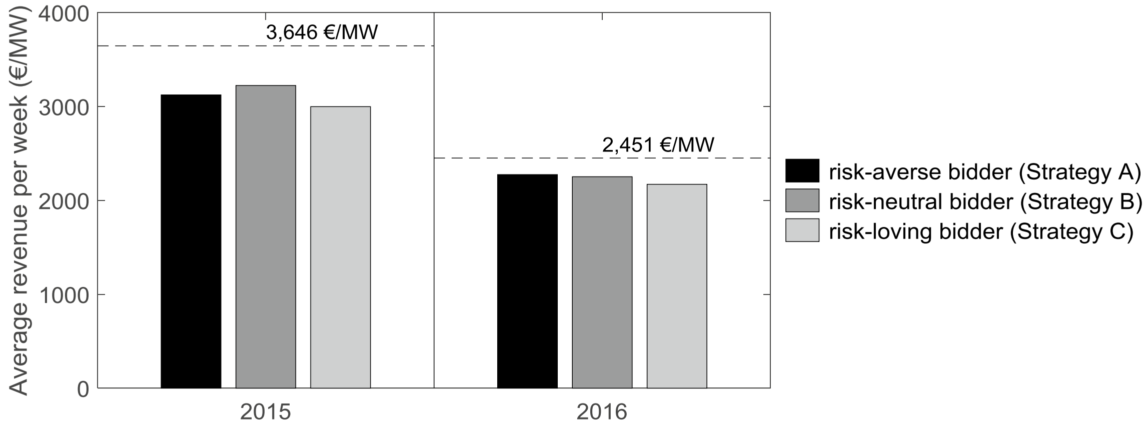

Fig. 9. Attainable average weekly revenues of a BESS offering 1 MW of PCR in the years 2015 and 2016 sorted by bidder type and average PCR price in the respective year (dashed line)

Fig. 9 compares the attainable revenues of the three bidder types for the price years 2015 and 2016. The results are normalized to average weekly values. In both years, the attainable revenues of the bidders are lower than the average PCR price. In 2015, a year with comparatively high PCR prices, the bidders' revenues are between 11 and 18 % lower than the average PCR price; in 2016, which was a year with relatively low PCR prices, the strategies seem to be more successful with a gap of 7 to 12 % between the bidders' revenues and the average PCR price. While the risk-neutral bidder achieved the highest revenue in 2015, followed by the risk-averse bidder with a difference of 3 %, the risk-averse bidder attained the highest revenue in 2016, followed by the risk-neutral bidder with a difference of 1 %. In both years, the risk-loving bidder achieved the lowest revenues. However, the differences in revenues between the strategies in the respective year are not significant.

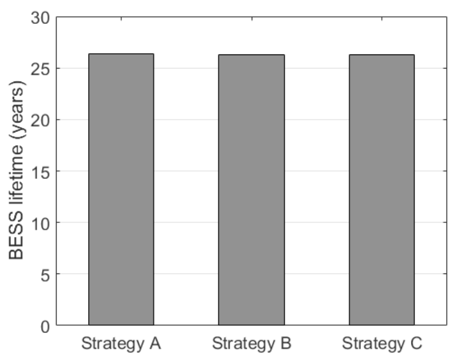

Fig. 10. Lifetime expectancies of the BESS for the different bidding strategies based on 2016 data

Fig. 10 illustrates the lifetime expectancies of the BESS for the different bidding strategies, which have been calculated by the simulation model. It can be seen that the differences in aging between the three strategies are negligibly small. In the aging simulations, the BESS reaches a lifetime of 26.37 years if strategy A is applied, 26.27 years if strategy B is applied, and 26.29 years if strategy C is applied.

These results indicate that the lifetimes calculated with the aging model are not sensitive to the chosen bidding strategies. Due to the shallow cycling, which is characteristic for the considered application, calendar aging is predominant. There is less cyclic stress on the battery with risk-loving strategy C due to several weeks a year, in which the battery is not used for PCR provision. The average SoC over the year is mostly within the range of 30-70 %, which causes moderate calendar aging. At SoCs of 90 % and higher, the aging rate increases drastically and leads to faster calendar aging. On the other hand, at SoCs of 15 % and lower, aging is noticeably slowed down. In the presented case this could lead to an additional capacity loss of up to 2 % over the whole lifetime if the battery was stored at full charge during weeks without PCR. Without the implementation of a "preserving" charge management that decreases the state of charge in weeks without PCR, there is no distinct difference in battery aging with regards to the chosen strategy. The average SoC in idle weeks without PCR provision is stochastically scattered in the same range between 30-70 % as in operational weeks, which can best be seen in Fig. 11. The spikes can be identified as idle weeks. The given distribution leads to almost identical calendar aging in weeks with and without PCR provision.

This might change if the battery was used for a secondary application in those weeks or with the above-mentioned practice of charge management. A secondary application with deeper depths of discharge, e.g. intraday arbitrage trade, would lead to different cyclic aging during several weeks per year and therefore influence the overall expected lifetime of the battery system. Using the BESS for intraday arbitrage trade during the idle weeks was not further investigated. The expected revenue generated on the intraday market in combination with the increased aging would reduce the economic feasibility of the BESS compared to PCR-only operation.

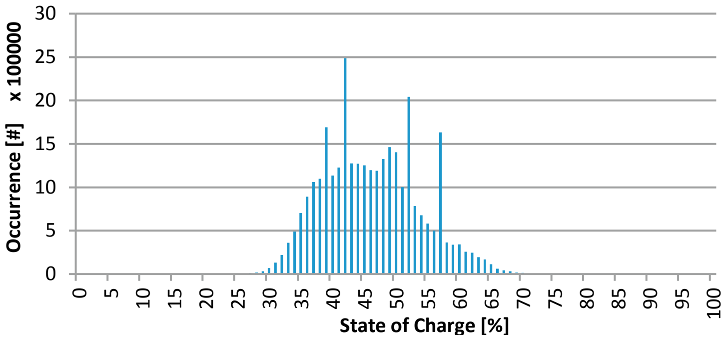

Fig. 11. Distribution of average State of Charge for Strategy C

The battery aging model was parameterized from high performance NCA (Nickel Cobalt Aluminum) lithium-ion cells with an exceptionally long calendar lifetime. This results in a relatively long battery life that exceeds guaranteed lifetimes of most manufacturers. However, this is heavily dependent on cell chemistry and quality. Expected lifetimes of a battery system solely used for PCR range from 15 to 20 years, with the total number of cycles over lifetime being less relevant, since cyclic stress is not the lifetime-limiting factor in this application.

3.2. Influence of PCR price development and year of system commissioning on the economic feasibility of BESS

In order to assess the economic feasibility of the BESS, the NPV at the end of the systems' lives (i.e. when 80 % of the original capacity remains) is calculated and used as comparative figure. If the NPV is negative, the investment will not be profitable, a positive NPV implies a profitable investment. System lifetimes between 15 and 30 years are considered in the assessment as this range is likely to cover the lifetimes of most commercial lithium-ion BESS. The years after 2025 are not considered since there are no price projections available for this time horizon

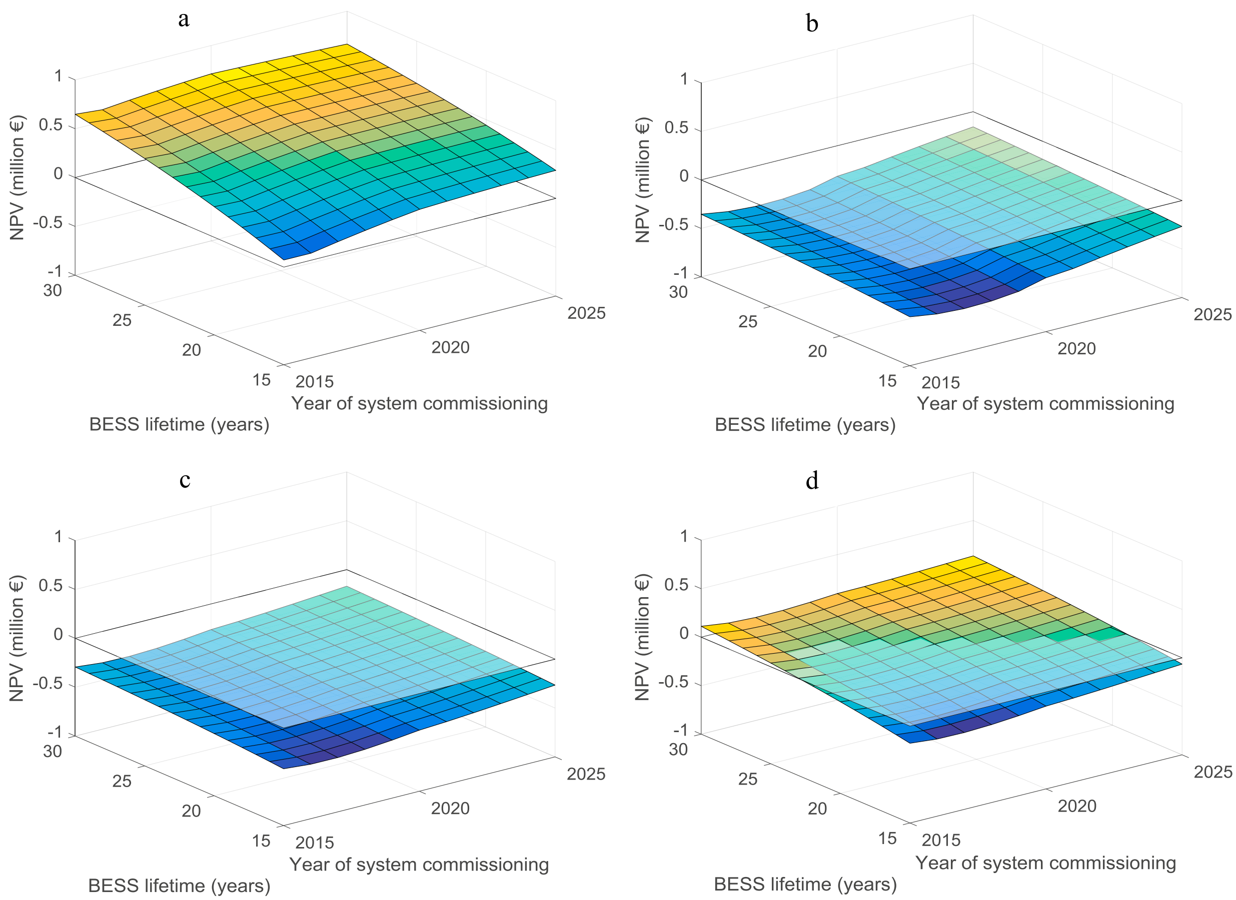

Fig. 12. NPV of a 1.5 MWh BESS providing 1 MW of primary control reserve assuming (a) a price jump to 2,500 €/MW, (b) a linear decrease, (c) an exponential decrease to 1,000 €/MW, and (d) an exponential decrease of PCR capacity prices to 1,500 €/MW

Fig. 12 compares the NPV at the end of system operation as a function of the assumed system lifetime and the year of system commissioning for the distinct PCR price scenarios. The year of system commissioning is the year, in which the investment is undertaken and the system starts operation. It reflects the system prices, which are assumed to decrease continually as described in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

In Fig. 12a, PCR prices are assumed to stabilize from 2016 on at a level of 2,500 €/MW. In this scenario, the NPV at the end of operation is positive regardless of the BESS lifetime and the year of system commissioning. The NPV increases with increasing BESS lifetime and later year of system commissioning.

In the scenarios with the linear and the exponential PCR price decrease to 1,000 €/MW (Fig. 12b and Fig. 12c), the considered BESS will not become an economically feasible option for PCR supply in the timeframe between 2015 and 2025 under the assumed economic framework. Between 2015 and 2017, the end-of-life NPV decreases due to rapidly decreasing PCR prices in these scenarios, which cannot be compensated by the simultaneously decreasing BESS prices. From 2018 on, decreasing BESS prices begin to compensate the price decline on the PCR market and the end-of-life NPV rises. However, it remains negative at least until 2025. The progression of PCR price curve (linear vs. exponential) seems to have only a minor impact on the end-of-life NPV. The long-term PCR price level and the BESS price development are observed to have a larger impact.

In the case of an exponential PCR price decrease to 1,500 €/MW (Fig. 12d), the investment in a BESS providing PCR can be either profitable or not, depending on the year of system commissioning and the BESS lifetime. If the BESS has a lifetime shorter than 18 years, the investment will not become profitable until 2025. If the BESS's lifetime lies between 19 and 22 years, the investment is not profitable yet, but the NPV will become positive eventually. BESS with a longer lifetime will become profitable earlier, starting with BESS with a lifetime of 22 years, which will be profitable when commissioned in 2021 or later. BESS with a lifetime between 23 and 25 years used to be profitable when commissioned in 2015 (systems with a lifetime of 25 years also in 2016). However, currently, an investment would not be profitable due to the sharp decrease of PCR prices. In the following years, when decreasing system prices compensate the price decline on the PCR market, BESS with a lifetime between 23 and 25 years will become economically feasible again. If the BESS lifetime exceeds 25 years, the system will be economically feasible regardless of the year of system commissioning. The BESS investigated in the aging simulations reached a lifetime of more than 26 years and will thus be economically feasible in this scenario regardless of the year of system commissioning.

Fig. 13 illustrates the marginal saturation prices for the linear-decrease scenario under the assumption of two 1 MW/1.5 MWh BESSs with lifetimes of 26 years (which is the result of the aging simulation, see Fig. 10) and 20 years (warranty usually given by cell manufacturers) as a function of the year of system commissioning. The saturation price is the price level, at which the PCR market price stabilizes after the linear-decrease period. These prices represent the lowest PCR price level, for which an investment in the respective year would still be profitable. If PCR prices fall to a lower level, the systems will lose profitability. Looking at it the other way round, the marginal saturation prices can be considered the lowest bid, which a bidder who invested in the respective year, can place in a PCR auction after the market price has reached saturation level. From the chart, it can be seen that, under the given assumptions, the BESS with a lifetime of 20 years, if commissioned in 2017, will continue to be economically feasible if the PCR capacity price does not sink below 1,929 €/MW per week. If such a system is commissioned in 2025, it will only be profitable if the PCR price remains on a level greater than 1,498 €/MW during its entire lifetime. If the BESS reaches a lifetime of 26 years, the NPV at the end of the system lifetime will be positive as long as the PCR price does not sink below 1,707 €/MW for a BESS commissioned in 2017 and below 1,348 €/MW for a BESS commissioned in 2025 respectively.

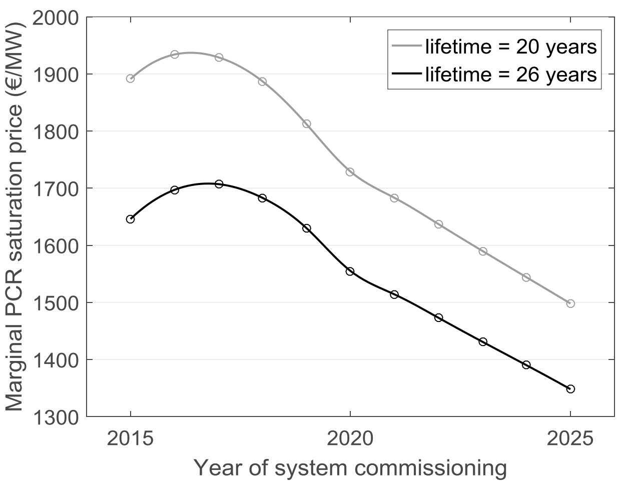

Fig. 13. Marginal saturation prices for PCR as a function of the year of system commissioning

4. Conclusion and outlook

The aim of this study was to determine the impact of different bidding strategies and price developments on battery aging and the economic feasibility of BESS providing PCR in the German control area. The results of the simulations underline again that battery aging in the PCR application is always dominated by calendar aging effects. In general, simple bidding strategies considering marginal battery cost allow for high acceptance quota in the PCR auctions. More aggressive strategies for the price bid will only lead to a smaller number of weeks with PCR provision and thus to fewer cycle numbers if no other service is provided. As the mean SoC of the system is not in high or low ranges where calendar aging could be increased, the idle weeks do not lead to a shorter battery lifetime. The availability of the BESS for secondary applications increases with rising willingness of the bidder to take risks. However, when assessing the economic utility of a secondary application, the impact of additional cyclic aging effects needs to be considered as this might be significantly higher than for the PCR application.

The development of the PCR price and the BESS price are the key factors influencing the economic feasibility of BESS providing PCR and determine the appropriate time of investment. As these parameters are highly uncertain, investments come with a high risk of loss.

In a scenario with a drop of the PCR price to 2,500 €/MW, the considered BESS, which has a power-to-capacity ratio of 1:1.5, will continue to be economically viable regardless of the year of system commissioning and the BESS lifetime. If PCR market prices drop to a level of 1,000 €/MW, the considered BESS will not become a profitable investment regardless of the year of system commissioning, the BESS lifetime, and the price path leading to this value. If PCR prices stabilize at a level of 1,500 €/MW, the economic feasibility of the considered BESS will depend on the year of system commissioning and the BESS lifetime. In case the BESS lifetime exceeds 25 years, the investment will become profitable regardless of the year of system commissioning.

The marginal saturation prices, which represent the lowest PCR price, for which an investment in the respective year would be profitable, have been calculated for system commissioning in the timeframe between 2015 and 2025. The highest marginal saturation price occurs in 2017 with a value of 1,707 €/MW. Subsequently, marginal saturation prices decrease to a value of 1,348 € in 2025.

More research is required to assess how the choice of the battery aging model influences the results of power provisioning over the lifetime of the BESS and, thus, the results of the economic evaluation. This could be further advanced in the field of applications by standardizing aging-related operational data of the battery system and making these data available for the battery system operator. Standardization and policy-making could help to increase the knowledge of the system operator about the battery system's behavior and actual state, and thus, to enhance operation and decision making.

Furthermore, load profiles for most future grid-connected battery applications are unknown as yet. Better knowledge of these load profiles and the development of standardized load profiles for specific applications in cooperation with grid operators would facilitate the assessment of BESS and enable benchmarking of battery aging models.

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