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Model-based economic assessment of stationary battery systems providing primary control reserve

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Abstract

Rapidly decreasing battery prices and high capacity prices on the German primary control reserve (PCR) market promote the attractiveness of battery energy storage systems (BESS) for primary control provision. In order to assess the economic feasibility in this application field, two case studies based on a 2 MWh BESS are performed. By coupling a PCR simulation model with a battery aging model, battery lifetimes are estimated. Costs and revenues occurring during the lifetime are calculated using the net present value approach. The results indicate that a BESS with a power-to-energy ratio of 1:2 is not economically feasible under the current framework. A BESS with a power-to-energy ratio of 1:1 will break even after approximately nine years of operation. Decreasing battery system prices are likely to increase the price pressure on the PCR market leading to decreasing revenues for PCR supply. Battery aging results suggest similar aging behavior for both systems presented due to the prevalence of shallow DoD cycles and the resulting predominance of calendar aging.

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Keywords: Primary control reserve; battery energy storage system; techno-economic assessment; battery aging; net present value approach

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1. Introduction

Technology development and rapidly falling battery system prices promote the attractiveness of battery energy storage systems (BESS) for different stationary applications on grid level. The ability to respond rapidly and precisely to frequency deviations makes BESS ideal candidates for primary control provision (PCP). Recently, the application of BESS on the German primary control reserve (PCR) market has seen a dynamic development regarding the number of BESS projects and the prequalified BESS power, which have been announced so far. Fig. 1 provides an overview of the market development in Germany for the period 2012 to 2017. The biggest project so far is a 90 MW project of the utility STEAG, which is planned to be realized at six different locations in 2016/2017 [2].

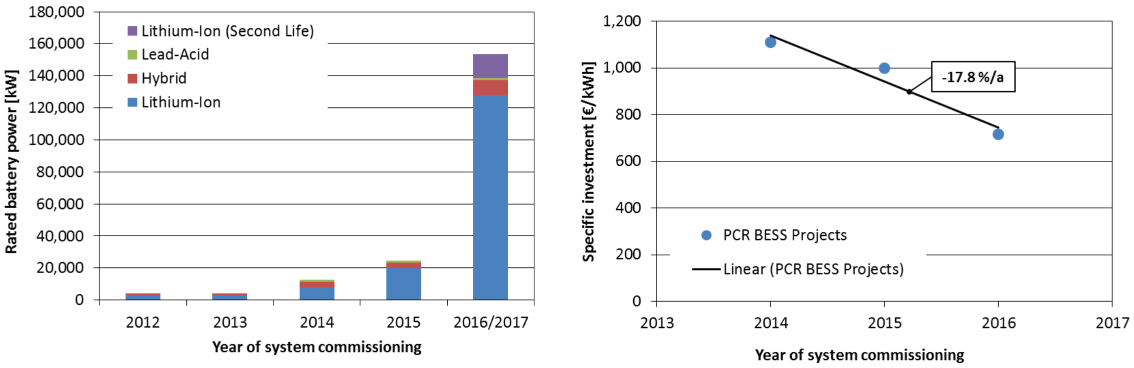

Fig. 1. Market development of BESS for PCR supply (left) and specific investment of selected realized or announced commercial BESS projects in Germany (right)

Under the assumption that all announced projects can be realized in time, the prequalified BESS power on the PCR market will reach approx. 155 MW by 2016/2017. Compared to the PCR market volume in Germany of 578 MW (2015) respectively 783 MW (2016), the market share of BESS can reach up to 27 %. Taking into account the coupled market area consisting of Germany, Austria, Switzerland and the Netherlands, the market share will reach 20 % if all BESS providers are accepted in the bidding process. Further projects in Austria, Switzerland and the Netherlands, which have not been considered in Fig. 1, might lead to an even higher market share. The market is currently dominated by Lithium-ion BESS. Stenzel et al. give an overview of recent BESS projects in Germany [3]. According to the dynamic market development the specific investment trend of realized or announced PCR BESS projects in Germany is also shown in Fig. 1. For the trend analysis, three commercial battery projects have been compared [2, 4, 5]. The trend between the first project in the year 2014 [5] and the recently announced project for the year 2016 [2] indicates a price decrease by approx. -17.8 %/a from 1,110 €/kWh (2014) to 710 €/kWh (2016), which is driven mainly by decreasing battery cell prices.

Nomenclature

BESS	battery energy storage system
C	capacity (MWh)
ch	charge
dis	discharge
DoD	depth of discharge (%)
DU	deadband utilization
E	energy (MWh)
EIS	electrochemical impedance spectroscopy
EoL	end of life
FCE	full cycle equivalents
i	discount rate (-)

Inv	investment (€)
LFP	lithium iron phosphate
LMO	lithium manganese oxide
LTO	lithium titanate
NMC	nickel manganese cobalt
NPV	net present value (€)
OF	overfulfillment
O&M	operation and maintenance
P	power (MW)
PC	primary control
PCP	primary control provision
PCR	primary control reserve
PQ	prequalified
SC	self-consumption
SoC	state of charge (%)
ST	schedule transaction
t	time (s)
T	battery lifetime (years)
VAT	value added tax
η	efficiency (-)

1.1. Literature review

The deployment of primary control reserve has been identified as one of the most suitable fields of applications for stationary battery systems [6]. A detailed description of the market for primary control and a description of degrees of freedom in Germany for BESS for PCR supply is provided in [7, 8]. The impact of the regulatory framework on BESS operation and design with a focus on technical aspects has been analyzed in [9]. A number of papers present techno-economic modelling approaches with different foci including a comparison of different battery types [10], a comparison between conventional power plants and BESS [11], the consideration of battery aging via different approaches [12-14] and the analysis of different BESS operation strategies [15]. Most of the papers use net present value (NPV) approaches for economic analyses. However, a detailed analysis of BESS costs and revenues over the battery lifetime under consideration of application specific battery aging and individual operation strategies regarding the degrees of freedom for BESS operation is still pending. Environmental impacts of BESS for PCR supply are assessed in [16].

1.2. Reseach objectives

Primary control is required to balance the feed-in and use of electricity to/from the grid, thereby ensuring safe and stable grid operation. In Germany, PCR is traded on a separate auction market with specific regulations. These regulations (minimum bid size of 1 MW, contract period of one week) offer the opportunity of a market entry for stationary battery systems and allow for a certain degree of flexibility regarding system configurations and operation strategies. However, little is known about how battery design and operation strategies influence costs and revenues occurring throughout the battery lifetime. Following a model-based approach considering Germany as a case study, a techno-economic analysis of stationary battery energy storage systems (BESS) providing primary control reserve (PCR) is conducted in this work. The effects of battery design and operation strategies adapted for primary control supply are investigated focusing in particular on lifetime costs and revenues under consideration of application-specific aging.

In order to calculate costs and revenues, the technical simulation is complemented with battery system prices and historic market data (intraday market data, PCR tendering results) of the year 2015. By contrasting investment and cost of operation with revenues obtained on the primary control reserve market, an economic assessment of the battery system is conducted. Furthermore, the current regulatory framework regarding levies and taxation is considered. Operation experiences from a realized BESS [5] are used to complement the assumptions if possible. These results lead to substantial conclusions regarding the cost-effectiveness of providing primary control through stationary battery systems.

In addition to the operating strategy and the battery lifetime, the price development for BESS with currently rapidly falling system prices and the related uncertainty regarding the future capacity price development on the PCR market have a major impact on the cost-effectiveness of BESS projects. With the entry of new market participants, the increasing competition is likely to trigger falling capacity prices in the PCR market [17], similar to the development observed in the secondary and tertiary control reserve markets [1, 18, 19]. Thus, the timing of the investment decision has a significant impact on the cost-effectiveness. As part of the analysis, therefore, the profitability of BESS, depending on the future development of battery system prices is assessed. Based on this, the marginal capacity price on the primary control reserve market is determined in dependency of the future BESS system price.

2. Methodology and basis data

2.1. General modeling approach

In this study, a BESS operation simulation model for the specific application of PCR [9] is combined with a Li-ion battery aging model based on experimental data gained from a large test matrix on 18650 NMC cells [20]. The simulation is time-discrete with a temporal resolution of one second. The overall model consists of three different parts: the grid frequency control module, the BESS operation simulation module and the statistical evaluation module. Fig. 2 shows the structure of the PCR simulation model.

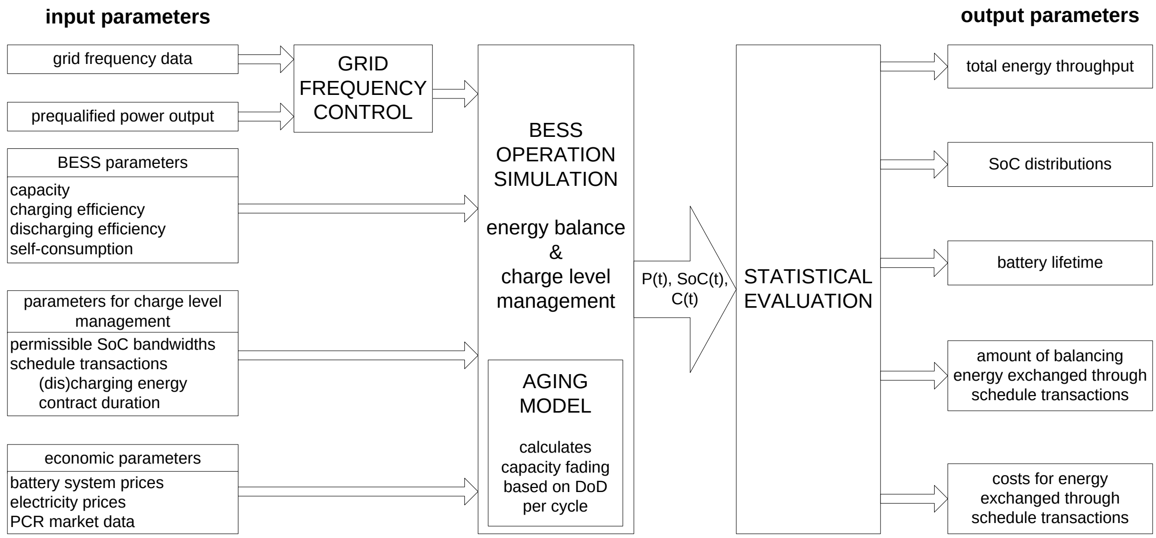

Fig. 2. Structure of the PCR simulation model with simplified aging model

Based on a grid frequency time series, the grid frequency control module calculates the required power output of a BESS, which is prequalified for participation in the PCR market and has successfully tendered for a PCR contract period with a certain power rating, for each second. The BESS operation simulation module calculates the BESS's reaction to the grid-side power demand and distinct measures of charge level management. The aim of these measures is to avoid that the BESS becomes inoperable (0 % and 100 % state of charge (SoC)). The aging model is integrated in the BESS operation simulation module. It simulates the capacity fading of the BESS due to electrochemical degradation processes. The simulation is run until a predefined end-of-life criterion (here 80 % of nominal capacity, C_{nom}) is reached. The output of the BESS operation simulation module includes time sequences of the power output, the SoC and the usable capacity of the BESS as well as data on schedule transactions on the intraday electricity market for charge level management. The statistical evaluation module analyzes the data generated by the BESS operation simulation module. It calculates the total energy throughput, SoC distributions and the battery lifetime. Furthermore, it records each schedule transaction and calculates the amount of energy exchanged through schedule transactions and the costs and revenues caused by these transactions.

2.2. The BESS operation simulation module

The core of the model is the BESS operation simulation module. The input data for the model include the grid-side power demand, which is calculated by the grid frequency control module, several technical parameters such as the nominal capacity, charging and discharging efficiencies and the BESS's self-consumption, and parameters for charge level management.

The regulatory framework of the German primary control reserve market allows providers to use a number of measures to adjust the BESS charge level. In this study, two grid-frequency dependent measures, overfulfillment of the required power output and deadband utilization, which have proven to be the most effective for charge level management, are considered. Furthermore, charging or discharging through schedule transactions on the intraday spot market can be used as a third option for charge level management. This option has the advantage of being independent from the grid frequency and of being able to choose an arbitrary amount of energy to adjust the BESS charge level. However, certain constraints like a minimum lead time of 30 minutes, before a schedule transaction can be performed, affect operational planning and battery design. All three options of charge level management described are implemented in the simulation model. A detailed description of the model and an impact analysis of different operation strategies can be found in [9].

The BESS is modeled as a 'black box', which encompasses the battery itself and all auxiliary devices required to establish the grid connection (inverter, transformer) and to ensure operability (air-conditioning). The system is described by a set of parameters including the battery capacity in terms of energy C(t) [MWh], its charging and discharging efficiencies (η_{ch}, η_{dis}), its self-consumption ΔE_{SC}, its charge level in terms of energy E(t) and state of charge SoC(t), and its power output $P_{BESS}(t)$.

The BESS operation module gradually calculates the energy balance for every time step. For the energy balance at the time t_k, the energy content $E(t_{k-1})$ of the BESS, the energy charged or discharged due to primary control (ΔE_{PC}), the additional charging or discharging energy resulting from the distinct measures for charge level management (ΔE_{OF} for overfulfillment, ΔE_{DU} for deadband utilization and ΔE_{ST} for schedule transactions) and the self-consumption of the BESS (ΔE_{SC}) are taken into account:

$$E(t_k) = E(t_{k-1}) + \Delta E_{PC}(t_k) + \Delta E_{OF}(t_k) + \Delta E_{DU}(t_k) + \Delta E_{ST}(t_k) - \Delta E_{SC} \quad (1)$$

Each term of the energy balance reflects the respective power output integrated over one time step:

$$\Delta E_i(t_k) = \int_{t_{k-1}}^{t_k} P_i \, dt_k \quad (2)$$

The assumptions for the technical parameters of the BESS and the parameters for charge level management in the simulations are listed in Table 1.

Table 1. Technical parameters of the BESS and parameters for charge level management

Parameter	Value
prequalified power for PCR supply	1 MW_{PQ} / 2 MW_{PQ}
rated power	1.8 MW / 3.6 MW
nominal capacity at start	2 MWh
charging efficiency	95 %
discharging efficiency	95 %
self-consumption	13.86 kW per MW_{PQ} [16]
SoC set point for overfulfillment and deadband utilization	50 %
upper SoC limit for schedule transactions	70 %
lower SoC limit for schedule transactions	30 %
contract duration for schedule transactions	15 minutes
power rating and energy exchange per schedule transaction for the 1 MW_{PQ}/2 MWh system	0.8 MW / 0.2 MWh
power rating and energy exchange per schedule transaction for the 2 MW_{PQ}/2 MWh system	1.6 MW / 0.4 MWh
end-of-life (EoL) criterion	80 % C_{nom}

2.3. Aging model

The effective capacity of a BESS fades over its lifetime due to aging, which can be categorized in calendar and cyclic aging. For an accurate determination of battery aging, a detailed battery model can be used as presented by [20]. It consists of a thermo-electrical model and an aging model. The former has been modeled based on electrochemical impedance spectroscopy (EIS) and simulates cell voltage and thermal losses as well as electrical losses caused by battery currents during operation. The latter has been parameterized through extensive cell measurements and uses the output of the thermo-electrical model for battery state of health determination.

Based on the complex aging represented in the battery model, a function describing the loss of battery capacity with cycle depth has been derived. This approach is based on stress and failure (S-N) curves introduced by Wöhler to determine the effect of cyclic stress put on a material or structural element. The S-N curve used for aging determination in the presented model combines cyclic and calendar aging and has been derived from a large scale test matrix on NMC 18650 cells. For an in-situ determination of the effect on the system economy this function has been integrated in the BESS operation simulation module (see Fig.). Thus, the model takes the changing overall performance of the BESS with increased battery age into account.

With the S-N curve approach, the correct classification of battery cycles becomes very important. The cycle counting mechanism has to determine the relevant macro- and microcycles, which are strained on the battery, to successfully compute the resulting cyclic aging. The implemented approach solely takes into account microcycles by counting the changes between positive and negative power delivered by the BESS. Superimposed macrocycles cannot be detected by this simple method; a more precise determination of cyclic aging demands for a detailed aging model with a more sophisticated cycle counting mechanism, e.g. Rainflow-counting. In the case of PCR, this means that aging is probably underestimated by the simulation, since a number of macrocycles are not accounted for. Still, the large majority of cycles in this application are very small cycles with less than 5 % DoD, so the error remains in an acceptable range.

2.4. Economic assessment

In order to assess PCR supply through stationary battery systems economically, costs and revenues occurring throughout the lifetime of the system are analyzed using the net present value (NPV) approach.

$$NPV(i,T) = -Inv_0 + \sum_{t=1}^{T} \frac{R_t}{(1+i)^t} \tag{3}$$

The NPV takes into account the investment Inv_0, the cash flow R_t occurring in a predefined time period t (one year in this study), the lifetime T of the BESS and the discount rate i. The cash flow R_t includes the operating and maintenance (O&M) costs, the costs and revenues of purchasing and selling balancing energy on the intraday electricity spot market, and the payments for PCR supply occurring during the respective year.

The investment Inv_0 for the BESS is strongly dependent on the year of system commissioning since battery system prices are currently decreasing fast. It includes a capacity-specific and a power-specific share:

$$Inv_0 = Inv_{cap} + Inv_{power} \tag{4}$$

The capacity-specific investment Inv_{cap} includes the battery cells, cell housing, cell connectors, battery module diagnostics, battery management system, cooling system and building. The power-specific investment Inv_{power} includes power electronics, transformers, contactors, fuses, control systems and air conditioning.

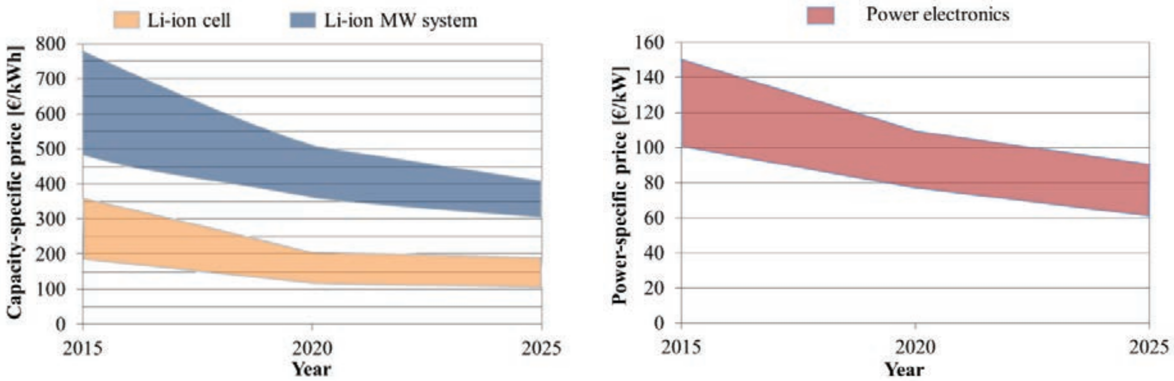

Fig. 3. Medium-term price development for Li-ion battery systems (left) and power electronics (right)

Fig. 3 presents the projected development of Li-ion capacity-specific system prices from 2015 to 2025. The prices are expected to fall below 450 €/kWh in 2020 and below 350 €/kWh in 2025 for MW scale systems. This estimation is valid for systems with LFP, LMO and NMC cells. These prices do not include software required for the energy management system. For the calculations in this study, power-specific system prices of 250 €/kW, 200 €/kW and 180 €/kW for the respective years 2015, 2020 and 2025 are assumed. Price development in this segment is expected to be mainly driven by power electronics, with a price range from 80-150 €/kW in 2015, decreasing to 60-90 €/kW in 2025 (Fig. 3). Prices for transformers, contactors, fuses, control systems and air conditioning are considered to remain constant (100€/kW) over the following ten years. They are included in the power-specific investment.

Regarding operation and maintenance, it is assumed that the BESS does not operate during two weeks of the year due to scheduled maintenance works. These operation downtimes are taken into consideration when calculating the revenue from PCR supply. Besides this, O&M costs are considered as an annual lump sum of 2 % of the investment Inv_0. Costs for an exchange of faulty battery modules are included herein.

The purchase and sale of energy through schedule transactions via the intraday spot market is likewise part of the annual cash flow. It is assumed that schedule transactions are settled in quarter-hourly contracts as they offer a higher degree of flexibility compared to hourly contracts. For this study, historical spot market data of the year 2015 as input time series for the entire simulation period have been used. The average price for a quarter-hourly contract in the year 2015 is 31.80 €/MWh, however, prices are extremely volatile with a standard deviation of 17.47 €/MWh and peak values reaching 236.35 €/MWh (maximum price) and -117.06 €/MWh (minimum price). Whenever the model simulates a schedule transaction, the respective price of the 2015 time series is used in the economic assessment.

The major part of revenues, which contribute to the annual cash flow, is generated by the payments resulting from PCR supply. The compensation of primary control provision is realized by provider-specific capacity price payments (pay-as-bid) according to the offered capacity price (€/MW).

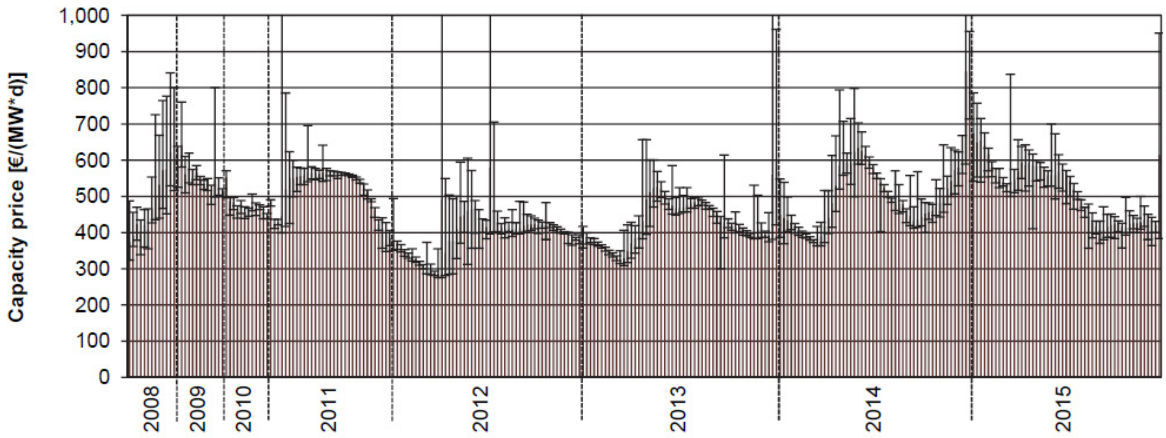

Fig. 4. Capacity price development (average, minimum and maximum values) on the German PCR market [1]

Fig. 4 shows the development of capacity prices on the German PCR market from 01-01-2008 onwards. The values are expressed as specific prices per day in order to make the prices comparable because the bidding period has been shortened from one month to one week as of 27 June 2011. The price development is relatively stable in the considered period. After the price drop in 2012, which occurred after the change of the bidding period length, prices recovered relatively fast and increasing prices can be observed from 2012 on. The price curves show a typical development with highest prices occurring during the summer months. According to the characteristic price development, periods for scheduled maintenance should be placed in periods with lower prices (e.g. spring). The yearly average capacity prices in the considered period are listed in Table 2.

Table 2. Average capacity prices (yearly average and yearly average range) on the German PCR market [1]

Year	2008	2009	2010	2011	2012	2013	2014	2015
Average capacity price per week [€/MW]	3,469	3,897	3,353	3,659	2,779	2,987	3,517	3,646
Average range of capacity prices neg./pos. [€/MW]	-501/ +885	-224/ +384	-140/ +111	-175/ +315	-253/ +679	-185/ +374	-292/ +485	-353/ +335

The average capacity price over the whole period from 2008 to 2015 is 3,413 €/MW. The range of capacity prices around the mean value is on average -265 and +446 €/MW. In order to calculate the revenues from PCR supply, the average capacity price of the year 2015 is considered. This implies a bidding strategy of aiming for the average capacity price, which is a rather conservative strategy with a high chance of placing a successful bid. Other strategies might aim at higher payments and therefore place bids with higher capacity prices, but take a higher risk of an unsuccessful bid.

Table 3 lists the basis data used for the economic assessment. Taxes and levies relevant for a battery system providing PCR in Germany are considered in the assessment. These include the value added tax (VAT), which is applied to revenues and expenses, but not to investments.

Table 3. Basis data for the economic assessment

Item	Value
capacity-specific investment	600 €/kWh
power-specific investment	250 €/kW
maintenance	2 % of investment per year
revenues from PCR supply	3,646 €/week (see Table 2)
costs/revenues from schedule transactions (based on 2015 spot market data)	vary for each transaction
value added tax (VAT)	19 %
tax on electricity (only applied to self-consumed energy)	20.50 €/MWh
charge for electricity metering	631.60 €/year [21]
discount rate	5 %

The development of prices both on the spot market and on the primary control reserve market is subject to great uncertainty. The assessment is based on historical price data, although this approach does not take possible price developments into consideration.

3. Results and discussion

In this section, simulation results of a BESS with a prequalified power rating and capacity rating of 1 MW_{PQ}/2 MWh ('1:2 dimensioned') are compared to those of a 2 MW_{PQ}/2 MWh ('1:1 dimensioned') system. The results include observations of aging behavior and an economic assessment of the two BESS systems.

3.1. Results for battery aging

Both battery systems show an expected lifetime of roughly 14 years. Still, the 2 MW_{PQ}/2 MWh system cannot provide the full prequalified power until its end of life. After 12 years of operation, the loss of available capacity leads to a derating of the system, thus the amount of PCR provided is reduced to 1 MW in the last two years of operation. Since the battery has reached the economical break-even after 8 years, this does not pose a problem for its profitability.

During its lifetime, the 1 MW_{PQ}/2 MWh system performs 3,945 full cycle equivalents (FCE). The number of FCE per year increases from 251 in the first year of operation to 312 in year 14. The 2 MW_{PQ}/2 MWh system performs 7,582 FCE during its lifetime. Here, the number of FCE per year rises from 526 in the first year of operation to 643 in the twelfth year, which is the last year of operation before the amount of PCR provided is reduced to 1 MW. Both systems perform almost 3.6 million partial cycles during their lifetimes. Although the number of FCE is substantially higher for the 2 MW_{PQ}/2 MWh system, system lifetimes are roughly the same for both systems. These findings suggest that calendar aging plays a more important role than cyclic aging in this application. Further investigation on this issue is required.

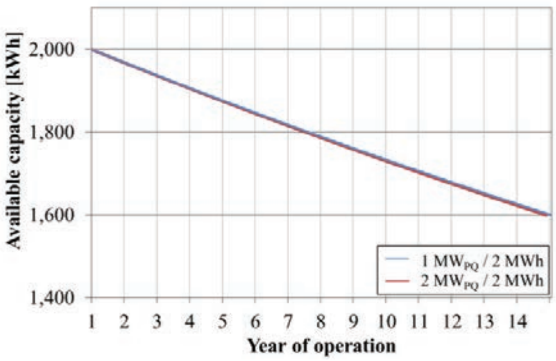

Fig. 5. Battery aging depicted as fade of available capacity

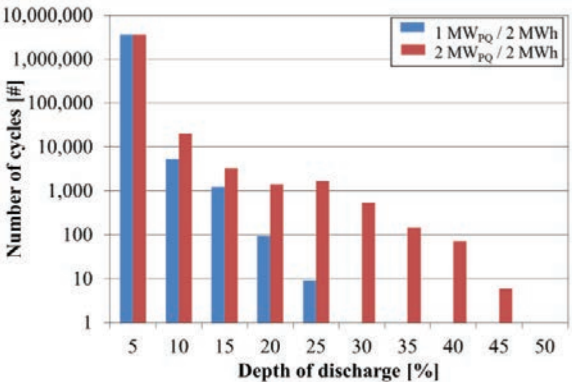

Fig. 6. Distribution of cycles during operation with respective depth of discharge

In terms of aging during simulation, there is hardly any difference between the two systems recognizable. Fig. 5 presents the capacity fade of both BESS showing almost identic aging behavior. The difference between the two systems can be described by the variation in DoD due to different BESS power ratings. Fig. 6 depicts the distribution of cycles strained on the battery systems over the full lifetime, clustered by depth of discharge, on a logarithmic scale. More than 99 % of all cycles occurring during the simulation have DoDs lower than 5 %, more than 95 % of all cycles have a DoDs even lower than 1 %. Within this DoD range, a high number of cycles can be realized before the EoL is reached. The rest of the occurring cycles have DoDs between 5 and 45 % for the 2 MW_{PQ}/2 MWh system and between 5 and 25 % for the 1 MW_{PQ}/2 MWh system. The small deviations in aging can be explained by the partly deeper cycles for the 1:1-dimensioned system.

3.2. Results of the economic assessment

Fig. 7 shows simulation results in terms of NPV for each year of operation. For the 1 MW_{PQ}/2 MWh system, the NPV remains negative throughout its entire lifetime under the given framework, i.e. this investment would not be profitable. The NPV of the 2 MW_{PQ}/2 MWh system becomes positive during the ninth year of operation, reaching an NPV of 0.77 million € at the end of its lifetime. The EoL criterion in this investigation has been chosen mainly based on experiences from existing stationary and mobile applications. For stationary applications, the EoL criterion may be adapted leading to longer payback periods with enhanced economic viability of the systems. It will be necessary to further investigate the aging behavior of batteries in this field focusing on a high voltage topology. The 80 % EoL capacity criterion tries to cover the intensified deviation between the cells in one string with increased aging.

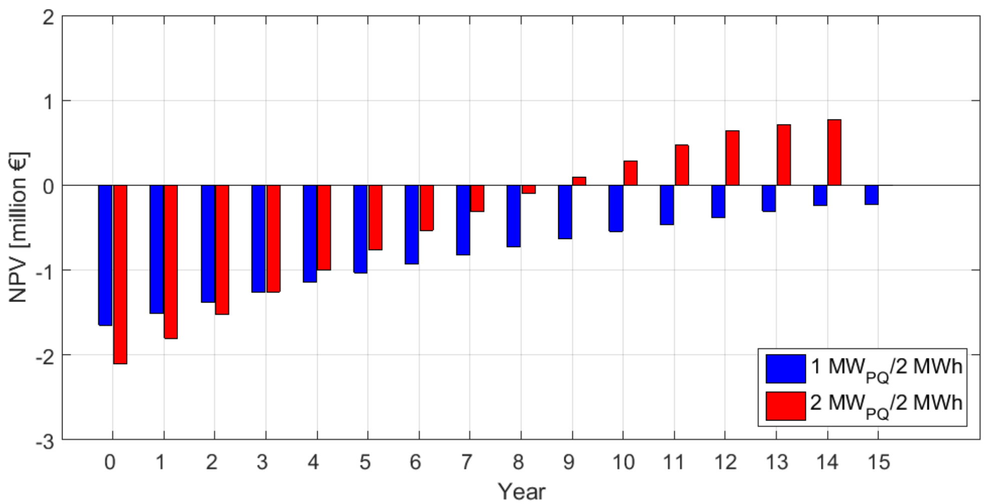

Fig. 7. NPV of battery systems providing PCR over their expected lifetimes – comparison of systems prequalified for 1 MW and 2 MW with 2 MWh capacities each

Fig. 8 visualizes the annual cash flows of the 2 MW_{PQ}/2 MWh system. The cash flows are dominated by the revenues obtained from providing PCR. Approximately 83 % of each annual cash flow from year 1 to year 12 is generated by payments for PCR supply. In the years 13 and 14, the revenues from PCR provision are reduced by half due to the fact that the prequalified PCR capacity decreases from 2 to 1 MW_{PQ}. Regarding the annual costs, it can be seen that maintenance and VAT make up the largest parts. All other components including purchase and sale of balancing energy on the intraday market contribute only small to the total annual cash flow.

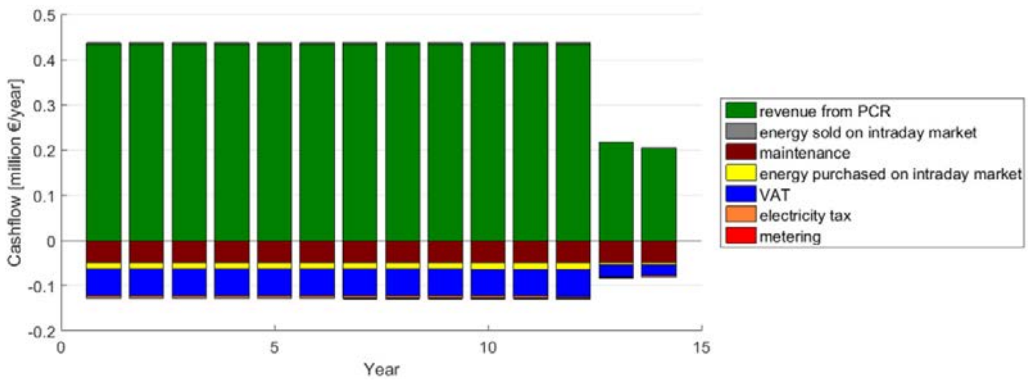

Fig. 8. Annual cashflows of 2 MW_{PQ}/2 MWh BESS

Fig. 9 shows the NPV as a function of the specific investment for the BESS under the assumption of a constant PCR capacity price of 3,646 €/MWh. As can be seen from the figure, the NPV at the end of the battery lifetime (14 years) decreases linearly with an increased specific investment for the battery system. The break-even for the 1 MW_{PQ}/2 MWh system is 729 €/kWh, which is less than the current specific investment for the system of 825 €/kWh (2015). The break-even for the 2 MW_{PQ}/2 MWh system is 1,337 €/kWh, which is significantly higher compared to the specific investment of 1,050 €/kWh for the system. The assumed specific investment in the calculations of both systems can be considered as rather conservative compared to the trend shown in Fig. 1. In addition to the current battery prices, the expected price development for the next ten years is presented in the graph.

In order to investigate the effect of more BESS entering the PCR market and falling BESS prices on PCR capacity prices, the development of the marginal PCR capacity price for a BESS operator is presented as well (Fig. 10). The marginal PCR capacity price is defined as the lowest price a BESS operator can offer at the PCR market and still achieve a positive NPV at the end of the system lifetime. Fig. 10 shows the decrease of the marginal PCR capacity price with decreasing specific investment for the battery system. Under the current economic framework (2015), a marginal PCR capacity price of 2,820 €/MW has been calculated for the 2 MW_{PQ}/2 MWh system. The marginal PCR capacity price of the 1 MW_{PQ}/2 MWh system is 4,108 €/MW, which is still higher than the current average PCR capacity price of 3,646 €/MW. Assuming that battery prices will drop to 450 €/kWh in 2020, which corresponds to a specific investment of 810 €/kWh, a marginal PCR capacity price of 2,206 €/MW for the 2 MW_{PQ}/2 MWh system can be expected. This would be a 22 % decrease in five years.

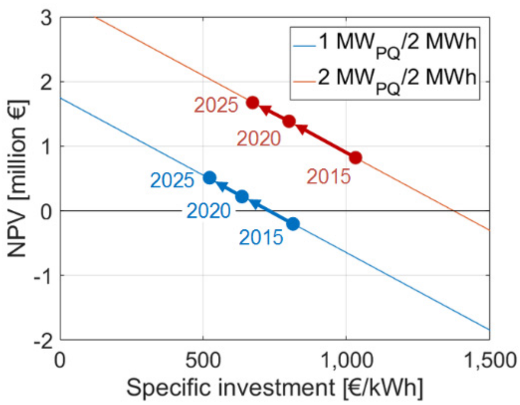

Fig. 9. NPV at the end of the battery lifetime as a function of the specific investment of the BESS

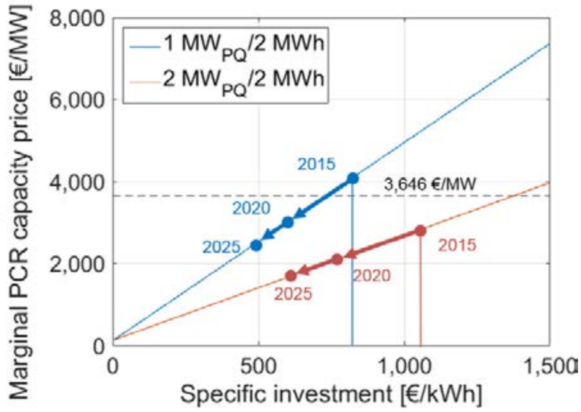

Fig. 10. Marginal PCR capacity price as a function of the specific investment of the BESS

The marginal PCR capacity price represents only a theoretical limit. No tenderer will be able to offer PCR for the marginal PCR capacity price in the long term, as such a bidding strategy would not generate any profit. However, the development of the marginal PCR capacity price gives an insight on how batteries might increase the price pressure on the PCR market and how prices in the market might develop consequently.

A recently published study [17] expects a decrease of PCR capacity prices in the near future caused by the market entry of new bidders including BESS operators. Based on the assumption of 155 MW additional PCR capacity [17], an average price decline of 20 % is projected in this study. In the resulting tension field of decreasing battery system prices leading to an increasing number of BESS projects and, thus, a rising market share on the one hand and growing competition with decreasing PCR capacity prices on the other hand, investment decisions come with a higher risk. In extreme cases, the development of battery system prices may lead to situations, in which BESS operators, who invested early, lose profitability as competitors, who invested later, are able to offer PCR at lower capacity prices.

In a second study [22], which has recently been published, it is assumed that 250 MW of additional PCR capacity provided by BESS enter the market. Instead of anticipating a certain bidding strategy, bids placed by BESS operators are assumed to be equal to the minimum bid of the respective contract period. The study suggests that, under this assumption, a sharp decline in the upper marginal PCR capacity price of up to 38 % in a few weeks of the year is possible. However, the average level of PCR capacity prices over a whole year is not expected to decrease strongly.

Optimizing the bidding strategy for the PCR market may lead to revenues higher than the yearly average capacity price, which the calculations in this paper are based on. The average capacity price obtained by WEMAG (a German power utility operating a 5 MW_{PQ}/5 MWh BESS for PCR supply) was 3,810 €/MW_{PQ} in the period from September 2014 to September 2015, which is 4.5 % higher than the yearly average capacity price in 2015 [23].

Overall, the development of the PCR market, the prices involved and the resulting possible revenues for BESS operators are difficult to predict since the bidding strategies of the market participants are unknown.

4. Conclusion and Outlook

Battery aging has been included through an S-N curve approach and a simplified cycle count algorithm. This allowed analyzing the changing performance of the BESS over time of operation on the PCR market. Due to the very shallow DoD cycles, the simple approach, which ignores the influence of current rates and temperature, cannot reveal the difference for the 1:2 and 1:1 dimensioned systems. Therefore, the next step in the investigation of BESS providing PCR will be the implementation of a more detailed battery aging model in the BESS operation simulation module. This will be essential for more accurate statements regarding system dimensioning and cost-effectiveness. However, the simulation has first proven that both systems can deliver the expected power output under the given framework at all times over their lifetime. Even the 1:1 dimensioned system can deliver the expected power output at all times during the payback period. However, during operation, it reaches critically high and low SoCs, which are currently not tolerated by the responsible TSOs.

The presented results show no business case under current market conditions for a system with a 1:2 power-to-energy (P/E) ratio on the PCR market. The break-even analysis signals a maximum specific investment of 729 €/kWh, which is below the 2015 market prices. If the P/E ratio is shifted closer to 1:1, the current system price will already fall below the break-even value.

In an extreme market scenario, a prolonged intensive degression of battery system prices can put early adopters out of business as the competing BESS, which have been installed later, can bid with a lower marginal capacity price. The analysis of the break-even values shows that BESS can offer PCR services at a minimum of 2,820 €/MW under the given assumptions. This might lead to overall lower capacity prices due to increased competition and bidding prices might decrease at maximum by a value of around 23 % compared to the 2015 average. However, this result has to be seen as an extreme value, which is not likely to be reached, since the assumed BESS dimensions might be inadmissible and the bidding strategy would not generate any profit for the BESS operator.

In the next step, the aging behaviour will be analysed using a more detailed aging model and a comparison to other battery technologies will be included. Moreover, parameters affecting the economic viability will be further investigated. This investigation will include a more detailed consideration of requirements claimed by the TSOs, an analysis of different bidding strategies for the PCR market, and the application of different end-of-life criteria.

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References

[1] German TSOs. Internet platform for control reserve tendering, 2015 [cited 08.12.2015], available: https://www.regelleistung.net/.
[2] STEAG. STEAG investiert in Versorgungsstabilität: Neuanschaffung von sechs Großbatteriesystemen mit zusammen 90 MW, 2015 [cited 18.12.2015], available: http://www.steag.com/s-pressemeldungen-detailansicht+M563bdbd2755.html.
[3] P. Stenzel, J. Fleer, J. Linssen, and S. Troy, Energiespeicher. BWK 5 (2015) 42-55.
[4] DREWAG. Sachsens erster, großtechnischer Batteriespeicher im Innovationskraftwerk Reick eingeweiht, 2015 [cited 18.12.2015], available: https://www.drewag.de/de/drewag/presse/dg_presse_pressearchiv.php?id=547.
[5] WEMAG. Europaweit erstes kommerzielles Batteriekraftwerk eröffnet, 2015 [cited 18.12.2015], available: https://www.wemag.com/ueber_die_wemag/presse/pressemeldungen/2014/09_16_Eroeffnung_Batteriespeicher.html.
[6] A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer. Value analysis of battery energy storage applications in power systems. 2006 IEEE/PES Power Systems Conference and Exposition. Atlanta, USA, 2006.
[7] Consentec GmbH. Description of load-frequency control concept and market for control reserves, 2014 [cited 26.05.2015], available: https://www.regelleistung.net/ip/action/downloadStaticFiles?download=&CSRFToken=981d5e3e-9988-43fa-92aa-3a2b02019217&index=Lv7TWb5YK4I%3D.
[8] German TSOs, Eckpunkte und Freiheitsgrade bei Erbringung von Primärregelleistung. Leitfaden für Anbieter von Primärregelleistung. 2014, German Transmission System Operators: 50Hertz, Amprion, Tennet, Transnet BW.
[9] J. Fleer and P. Stenzel, Impact analysis of different operation strategies for battery energy storage systems providing primary control reserve. Journal of Energy Storage Article in press. (2016). DOI: http://dx.doi.org/10.1016/j.est.2016.02.003.
[10] A. Oudalov, D. Chartouni, and C. Ohler, Optimizing a Battery Energy Storage System for Primary Frequency Control. IEEE Transactions on Power Systems 22 (2007) 1259-1266.
[11] R. Hollinger, L. M. Diazgranados, and T. Erge. Trends in the German PCR market: Perspectives for battery systems. 12th International Conference on the European Energy Market (EEM), 2015. DOI: http://dx.doi.org/10.1109/EEM.2015.7216661.
[12] M. Swierczynski, D. I. Stroe, A. I. Stan, and R. Teodorescu, Primary frequency regulation with Li-ion battery energy storage system: A case study for Denmark, IEEE ECCE Asia Downunder (ECCE Asia 2013). 2013
[13] M. Swierczynski, D. I. Stroe, A. I. Stan, R. Teodorescu, and D. U. Sauer, Selection and Performance-Degradation Modeling of LiMO2/Li4Ti5O12 and LiFePO4/C Battery Cells as Suitable Energy Storage Systems for Grid Integration With Wind Power Plants: An Example for the Primary Frequency Regulation Service. IEEE Transactions on Sustainable Energy 5 (2014). DOI: http://dx.doi.org/10.1109/tste.2013.2273989.
[14] M. Swierczynski, D.-I. Stroe, A.-I. Stan, R. Teodorescu, R. Laerke, and P. C. Kjaer, Field tests experience from 1.6MW/400kWh Li-ion battery energy storage system providing primary frequency regulation service, IEEE PES ISGT Europe 2013. 2013
[15] S. Gerhard and F. Halfmann. Entwurf einer Betriebsstrategie für Batteriespeicher zur Teilnahme am Primärregelleistungsmarkt. Nachhaltige Energieversorgung und Integration von Speichern (NEIS 2014), Helmut-Schmidt-Universität, Hamburg, 2014.
[16] P. Stenzel, J. C. Koj, A. Schreiber, W. Hennings, and P. Zapp, Primary control provided by large-scale battery energy storage systems or fossil power plants in Germany and related environmental impacts. Journal of Energy Storage (2016). DOI: http://dx.doi.org/10.1016/j.est.2015.12.006.
[17] Pöyry. Primärregelleistung durch Batteriespeicher: Preisverfall erhöht Investitionsunsicherheit, 2016 [cited

18.01.2016], available: http://www.poyry.de/de/news/primaerregelleistung-durch-batteriespeicher-preisverfall-erhoeht-investitionsunsicherheit.
[18] J. Haucap, U. Heimeshoff, and D. Jovanovic, Competition in Germany's Minute Reserve Power Market: An Econometric Analysis. Energy 35 (2014) 137-156. DOI: http://dx.doi.org/10.5547/01956574.35.2.7.
[19] T. Pesch and P. Stenzel. Analysis of the market conditions for storage in the German day-ahead and secondary control market. 10th International Conference on the European Energy Market (EEM 2013). Stockholm, Sweden, 2013. DOI: http://dx.doi.org/10.1109/eem.2013.6607384.
[20] J. Schmalstieg, S. Käbitz, M. Ecker, and D. U. Sauer, A holistic aging model for Li(NiMnCo)O2 based 18650 lithium-ion batteries. Journal of Power Sources 257 (2014) 325-334. DOI: http://dx.doi.org/10.1016/j.jpowsour.2014.02.012.
[21] Westnetz GmbH. Entgelte für Netznutzung, 2015 [cited 07.01.2016], available: http://www.westnetz.de/web/cms/mediablob/de/2290308/data/1625980/9/westnetz/netz-strom/netzentgelte/archiv-netzentgelte/Netznutzungspreise-gueltig-vom-01.01.15-bis-31.12.15-.pdf.
[22] enervis, Wie viel Batteriegroßspeicher verträgt der Primärregelleistungsmarkt? enervis energy advisors GmbH, Berlin, 2016.
[23] WEMAG. WEMAG investiert weiter in sichere Versorgung im Stromnetz, 2015 [cited 18.12.2015], available: https://www.wemag.com/ueber_die_wemag/presse/pressemeldungen/2015/PM_2015_56_WEMAG_sichere_Versorgung.html.