Battery Energy Storage System Lifetime prediction for Grid-Booster Applications

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Abstract—**Grid boosters are an elegant option to reduce the grid expansion needed for the energy transition by optimizing it. This study examines how battery grid boosters can be designed more economically and seeks to predict their lifespan for different design variants. In the context of this work, calendar and cycling aging models for battery degradation are applied to the special application of a battery energy storage system, used as a grid booster. The difference to conventional battery systems is the small number of cycles in its lifetime. So smaller capacity degradation is assumed. The calculations predict a lifetime of 25 years, for a grid booster, compared to 15 to 20 years of a conventional system. So already a longer lifespan, as the needed 23 years for amortization, can be reached. The calculations show that by using a lower state of charge and a lower storage temperature in the idle times, the lifespan can be extended and so an increase of economic efficiency can be realized. To aim for a higher return on invest, a dual-use approach is discussed. Through the trade-off between more cycles and lifetime, economic viability can be achieved after 16 years.**

Index Terms—**Grid Booster, Lifetime prediction, Battery Energy Storage System, increase economic efficiency**

I. INTRODUCTION

The rapid expansion of renewable energy sources (RES) is causing issues in the power grids of many countries. Since wind energy currently represents the main source of electricity generation in Germany [1], a north-south imbalance has emerged, necessitating grid expansion. The grid expansion planned by the transmission system operator (TSO) is guided by the NOVA principle [2], which states that optimization and reinforcement should be prioritized before constructing new lines. One additional way to increase the load capacity of power lines is through so-called "grid boosters" [3]. These ensure that the N-1 security criterion is still met while allowing for higher line loads. Grid boosters are described in various forms [3], but generally consist of a source and a sink, typically implemented using large-scale battery energy storage systems (BESS) [4]. If a fault occurs in one of the involved grid components N, the booster can temporarily cover the energy demand. The power grid between these zones is not continuously operating at maximum capacity, the booster only engages in case of a fault event and thus only a few full load cycles per year occur. This clearly distinguishes the BESS in this work from other battery systems, for example for load shifting during the peak load hours of a day, which usually go through several hundred cycles per year. So far, there is no proof of the economic viability of grid boosters. This study examines whether battery lifespan in specialized grid booster applications could be inherently longer and how optimized parameters might further extend it. Additionally, we explore the potential benefits of energy market participation for economic efficiency.

To estimate battery lifespan, we use literature-based models, distinguishing between calendar and cyclic aging. This enables specific recommendations for battery booster operation.

The remainder of the present paper is organized as follows: The study begins with a review of related work in Section II, followed by the methodology, in Section III. The results are then presented and discussed in Section IV. Finally, we provide recommendations to improve the economic efficiency of boosters in Section V.

II. RELATED WORK

Lindner et al. provide a good overview of BESS-based grid booster [5]. Westermann et al. analyze and categorize curative actions, including grid boosters [6]. Porst et al. simulate the grid booster in DIgSILENT PowerFactory and demonstrate its impact on the grid in two scenarios [7]. The German TSOs, Transnet BW and Amprion are implementing grid boosters in different designs and aim to address open questions by their application [8],[9],[10]. They describe that it is desirable to achieve both a short response time and a high operational time. BESS are characterized by short response times, but have a shorter operational time compared to pumped storage power plants or gas turbines [5],[11]. As part of the HydrogREnBoost project, an attempt is being made to address the dilemma of very short response times and long operational times by combining the BESS and a hydrogen gas turbine [12]. None of the previously mentioned studies and initiatives provide a clear assessment of the lifespan of a booster in its special function. The present paper closes this gap.

III. METHOD

Naumann et al. [13],[14] have derived experimental degradation models for $LiFePO_4$ batteries . The cyclic aging and the calendar aging are calculated separately and then added to calculate the total aging, as described in Equation (1). Combined Aging Model [13],[14]:

$$Q_{\text{loss}}^{\text{comb.}}[\%] = Q_{\text{loss}}^{\text{cyc.}} + Q_{\text{loss}}^{\text{cal.}} \tag{1}$$

They also discuss the limitations of the models. For the application of cyclic aging, the temperature influence $k_T^{cyc.}$ is neglected ($k_T^{cyc.}$ is assumed to be 1), since the measurements are only carried out between 25°C and 40°C. In addition, test points with a Depth of Discharge (DoD) below 80%

show uneven aging trends in which lost capacity is partially restored. Naumann et al. [13] write that this phenomenon needs to be investigated in more detail. Equation (2) describes the cyclic aging, where the number of Full Equivalent Cycles (FEC) enter the equation with the power of $z^{cyc.}$.

Cycle aging [13]:

$$Q^{\text{cyc.}}_{\text{loss}}[\%] = k^{\text{cyc.}}_{T} \cdot k^{\text{cyc.}}_{C-Rate} \cdot k^{\text{cyc.}}_{DoC} \cdot \text{FEC}^{z^{\text{cyc.}}} \tag{2}$$

Equation (3) describes the DoD dependent parameter k_{DoC}.

$$k^{\text{cyc.}}_{\text{DoD}}(\text{DoD}) = c^{\text{cyc.}}_{Q_{\text{loss}}}(\text{DoD} - 0.6)^3 + d^{\text{cyc.}} \tag{3}$$

Equation (4) shows the parameter k_{C-Rate}, in form of a linear function, dependent on the C-Rate.

$$k^{\text{cyc.}}_{\text{C-Rate}}(\text{C-Rate}) = a^{\text{cyc.}} \cdot \text{C-Rate} + b^{\text{cyc.}} \tag{4}$$

Equivalent to cyclical aging, Equation (5) describes calendar aging. The time t in months is incorporated into the degradation through the square root[14]:

$$Q^{\text{cal.}}_{\text{loss}}[\%] = k^{\text{cal.}}_{\text{T}}(T) \cdot k^{\text{cal.}}_{\text{SoC}}(\text{SoC}) \cdot \sqrt{t} \tag{5}$$

In contrast to cyclic aging, temperatures outside the range between 25°C and 40°C can also be used for calendar aging. The temperature dependence is described by Equation (6), where the activation energy E_a is described by the Arrhenius equation based on the measurements [14].

$$k^{\text{cal.}}_{\text{temp}}(T) = k^{\text{cal.}}_{\text{ref}} \cdot \exp\left(-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right) \tag{6}$$

The State of Charge (SoC) has a major impact on calendar aging and is described by Equation (7).

$$k^{\text{cal.}}_{\text{SoC}}(\text{SOC}) = c^{\text{cal.}}(\text{SoC} - 0.5)^3 + d^{\text{cal.}} \tag{7}$$

All other parameters are listed in Table I. More detailed explanations can be found in [13], [14] and [15].

TABLE I
PARAMETERS FOR CYCLE AGING [13] AND CALENDAR [14] FOR Q_{LOSS}.

Parameter	**Calendar Aging** i = cal.	**Cycle Aging** i = cyc.
T_{ref}	298.15 K	–
SOC_{ref}	100%	50%
C-Rate	–	1
k_{ref}	$0.0012571\,\% \cdot \text{s}^{-0.5}$	–
a^i	-2059.8	0.0630
b^i	9.2644	0.0971
c^i	2.8575	4.0253
d^i	0.60225	1.0923
$z^{\text{cyc.}}$	–	0.5
E_a	$17.126\,\text{kJ} \cdot \text{mol}^{-1}$	–

Naumann et al. [14] describe that the limitations of the calendar model are primarily at extreme values for temperature and SoC. The measurements for the calendar model are conducted within a temperature range of 0°C to 60°C. The low temperatures of 0°C and 10°C are only measured at a SoC of 50%, whereas 25°C, 40°C, and 60°C are recorded at 0%, 50%, and 100% SoC. Thus, the limitations of the model can also be attributed to these conditions. These equations can be implemented, allowing the calculation of the special application of a grid booster, which is used only a few cycles per year and simultaneously has long weather-dependent and therefore predictable idle periods.

To verify the models of Naumann et al. [13],[14], the individual models are first compared with the publication results. The models are also compared to several datasheets from BESS companies [16],[17],[18],[19]. The models show degradations similar to the values presented in the data sheets for a given usage.

IV. RESULTS AND DISCUSSION

In the context of this work, two aging models are combined and applied to the specific case of a grid booster. This chapter discusses the lifetime of a grid booster and the potential ways to improve the cost-effectiveness. First, the improvement through avoiding calendar aging is presented. Afterward, a dual use-approach is taken into account.

A. Parameter definition - Regular Case

Battery systems have a higher degradation rate when they are used with a high DoD, as can be seen in Equation (3). Storing a battery with high SoC also means a high aging rate (Equation (7)). In the system design, manufacturers block a certain capacity. This means that the available capacity for the end user is between 80% and 95% SoC [20],[21]. Regularly, there is a blocked capacity in the area of small SoCs to avoid deep discharge and also at high SoCs, so no high voltages appear. If the models are calculated for example with 100% SoC and DoD the lifespan is just between several months (6000 cycles) and 8 years (0 cycles). This is why in this work it is assumed that the SoC is 85% and the DoD is 80%, what means that SoC never falls under 5% and also never rises over 85%. Battery container are normally equipped with temperature control, so the temperature is assumed to be 25°C in a first step. The End of Life (EoL) can be defined to 80% of the initial capacity of 85% SoC, what means related to 100% (100% - 85% · 80% = 32%) a degradation of 32% is assumed. Figure 1 shows a contour plot for the combined degradation models, with the EoL curve in red.

The confirmation of the Electricity Grid Development Plan from 2022 discusses the amortization and costs of the planned grid boosters in Kupferzell, Ottenhofen and Audorf [22]. They predict an amortization within 23 years. The aim would be an amortization within 15 years. By evaluating Figure 1 the advantage of the grid booster gets clear, because it is estimated with few FEC per year. Both an overload scenario and a grid failure must appear to trigger the booster application. Even if a conservative prognosis with once a week usage over 23 years, there would be less than 1300 cycles (dash-dotted). Figure 1 shows a lifespan of 25 years for this assumption. A more realistic scenario would be 700 cycles (dashed), which would

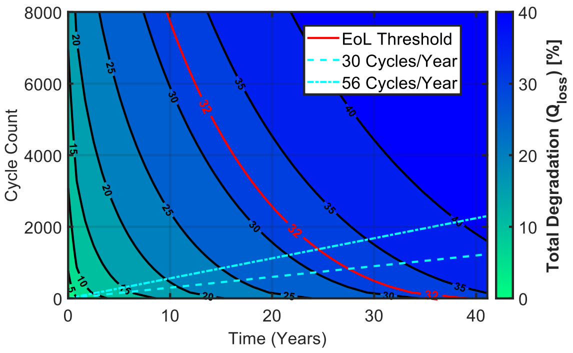

Fig. 1. Contour Plot of Battery Degradation (25.0°C, SoC = 85.0%, DoD = 80.0%)

predict then 28 years before EoL. So both assumptions would build an economical, valid business case for the grid booster with the parameters as described in this chapter in combination to the description from Electricity Grid Development Plan 2022 [22].

The Equations (5), (6) and (7) can be used to give advice for a longer lifespan, without additional costs, because sessional idle times can appear in booster applications. For example, if the booster is primarily used for high grid loads in case of wind energy transport from north to south in Germany, then these situations will emerge primary in late autumn, early spring and winter.

B. Lower State of charge in idle times

In times when the grid does not need the booster function, the BESS can discharge to a lower SoC to take care of the capacity degradation through calendar aging. Figure 2 shows the new threshold in case the calendar aging would always be at 42.5% SoC (50% of 85%). The red dashed line represents the threshold from Figure 1 for comparison. In the booster application, a few cycles are needed, what means in there we would have to charge the BESS up to 85 % SoC. So the true EoL lies between these two red lines. If the booster will be discharged in the idle times, without any additional costs, the lifetime lies between 25 up to over 35 years.

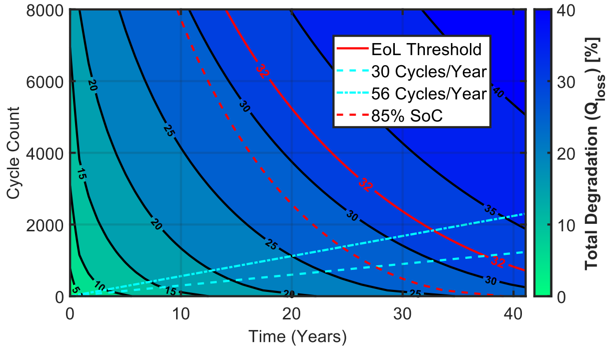

Fig. 2. Contour Plot of Battery Degradation (25.0°C, SoC = 42.5%, DoD = 80.0%)

After Equation (5) not only the SoC has an impact on the calendar aging, also the temperature does.

C. Cooler atmosphere in idle times

The temperature dependency is described for calendar aging in Formula (6). Smaller temperatures lead to lower degradation. To achieve lower storage temperatures, the BESS could, for example, be actively cooled at the cost of additional energy demand. Another possibility would be, to build the BESS underground, with expected ground temperatures of 7-10°C at 1.5 m depth [23]. In times when the booster function is needed, higher temperatures like 25°C would be more favorable. The calendar aging model is calculated with a temperature of 10°C. Figure 3 shows the impact of the temperature and predicts a battery lifetime between 25 and 50 years.

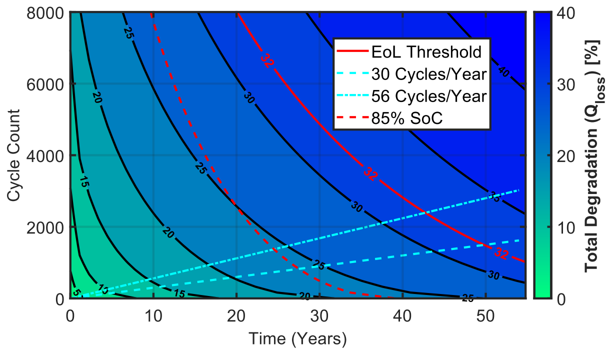

Fig. 3. Contour Plot of Battery Degradation (10.0°C, SoC = 85.0%, DoD = 80.0%)

It is clear that batteries experience lower degradation during storage when they are stored at lower temperatures. Of course, both parameters can put into the equations.

D. Combination of lower state of charge and temperature

By combining the two parameters SoC and temperature, even a longer lifespan is predicted. Theoretical a lifespan between 25 and over 65 years would then be possible. These projections are higher than what manufacturers currently guarantee, making them rather questionable, as for example other components such as the semiconductors in the power electronics might show degradation, which are not considered by the battery cell model. The question arises whether the models take all parameters into account, and whether it is actually possible to achieve such a lifespan. Another possibility to get a higher economic efficiency is to run a multi-use approach for the booster, to increase the income in a trade of by reducing lifetime through more cycles.

E. Participation on the energy marked in the idle times

Using the capacity during idle times for participation in the energy market generates revenue. This naturally leads to a significant increase in the number of cycles, which represents a major difference compared to the previously considered scenarios. A dual-use approach is mentioned in [22], taking into account § 11a (2) of the German Energy Industry Act

(EnWG). Some manufacturers guarantee for a conventional used BESS a lifetime up to 20 years with at least 4000 cycles [16],[18],[24]. The Boosters in Kupferzell, Ottendorf, and Audorf are planned with a total Capital expenditures (CAPEX) of 250 million € in 2025 for the 450 MW (450 MWh) units [22]. After 15 years, the savings would still be significantly below the estimated costs. The grid booster would only amortize after 23 years. The estimated additional annual costs are estimated with 2.0 million € per year, as can be seen in Figure 4. By assuming additional 200 cycles per year and a price delta of 62 €/MWh with 450 MWh additional 5.58 million € could be generated [25], shown by the green dashed line. All curves are extended until 2050 for comparison with the initial business case from [22]. In Figure 4, it can be seen that profitability can be achieved within 16 years using a dual-use approach. Figure 5 shows that the lifespan would also reach a lifetime between 16 and 17 years with 200 additional cycles.

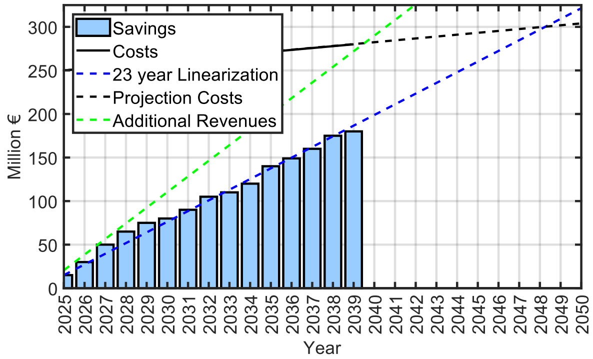

Fig. 4. Cost-benefit representation of the grid boosters in Kupferzell, Ottenhofen and Audorf (450 MW, 450 MWh) over 15 years (2025-2039). The costs cannot be amortized during this period and will only break even after 23 years (Estimated from [22]). Additionally, the green dashed line is shown, representing the estimated possible revenues that could be generated by gentle cycles for the booster (200 additional Cycles per year, Price delta of 62 €/MWh, 450 MWh Storage capacity).

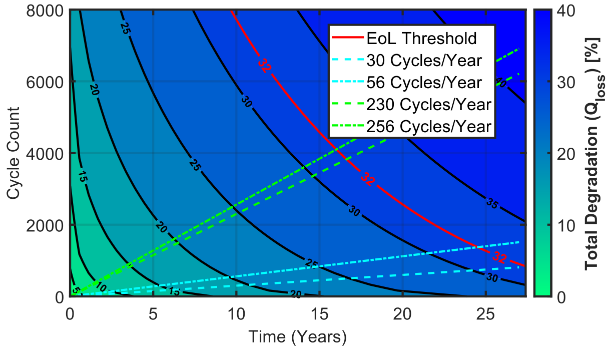

Fig. 5. Contour Plot of Battery Degradation (25.0°C, SoC = 85.0%, DoD = 80.0%) with 200 additional cycles per year for participating on the energy marked.

With an additional 200 cycles, idle times would be significantly reduced. Thus, the previous improvements are not included in this dual-use approach, but they could still be implemented additionally.

V. Conclusions

Battery grid boosters can be a valuable option for optimizing the power grid, potentially reducing the need for grid expansion and making the energy transition more cost-effective and faster. Redispatch costs can be minimized, and the share of renewable energy can be increased [26]. In the present paper, we demonstrate that the lifespan of BESS boosters exceeds the required amortization period, thus presenting a viable business case. Furthermore, the models of Naumann et al. [13],[14] reveal two options for extending the lifespan of battery boosters by reducing capacity degradation in idle times – either through lower temperatures and/or a reduced state of charge. The lifespan is predicted to be between 25 and 28 years, and thus exceeds 23 years from [22]. The model equations predict a high dependence for calendar aging to SoC. If the SoC in the idle times is discharged to 42.5 % the degradation rate for the booster is predicted to be lower so it could theoretical reach a lifespan somewhere between 25 and 35 years as shown in Figure 2. An even stronger impact has the storage temperature in the idle times. It is predicted somewhere between 25 and 50 years. While the change of the SoC can be done easy without additional costs, cooling down the hole battery containers requires additional cooling effort or an underground application, so higher CAPEX. In theory, the greatest improvement would result from a combination of a cooler storage environment and a lower SoC. However, it is questionable whether the model equations remain valid for long time periods between 25 and 65 years. For such estimates into the distant future, the uncertainties are growing considerably.

After adjusting the key parameters for calendar lifetime, a dual-use approach is proposed. This approach significantly improves economic efficiency by enabling participation in the energy market, by an additional 200 cycles. A high return on invest can be realized, and the booster gets economical efficient within 16 years, which is probably the highest interest of the investors.

VI. Outlook

The models presented in this work provide a simplified representation, as the focus is currently on cell chemistry. A grid booster consists of significantly more system components, and both the battery model and other elements should be expanded or optimized for a more detailed analysis. We present only individual possibilities for improvement. A comprehensive optimization that combines all potential enhancements could be part of future work.

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