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Primary Frequency Regulation with Li-Ion Battery Based Energy Storage System - Evaluation and Comparison of Different Control Strategies

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Abstract

The increased grid penetration levels of renewable sources are at the expense of the conventional power plants. This means that the grid support functions, traditionally achieved by the conventional power plants, need to be provided by new technologies. Since grid support with energy storage devices is becoming more attractive, the aim of this paper is to analyse the viability of providing primary frequency regulation with Lithium-ion based energy storage systems. Three control strategies of the energy storage system are analysed and compared in terms of economic benefits on the Danish energy market. The revenues and degradation of the Lithium-ion batteries are obtained by simulations. Furthermore, an energy management strategy based on variable state-of-charge (SOC) set-point is evaluated. Preliminary, the influence of different state-of-charge levels on the cycle lifetime is estimated. Finally, the economic analysis is based on simulations performed with different bidding ratios, i.e. different SOC set-points, for primary upward and primary downward frequency regulation. The results showed that all three control strategies were associated with considerable economic benefits even though different degradation levels of the Lithium-ion batteries were observed. Furthermore, it was found that the economic benefits are declining by increasing the batteries' SOC set-point.

1 Introduction

Nowadays the trends are moving towards renewable energy sources and distributed generation. This is on expense of the conventional centralized power plants, which share of power supply is correspondingly decreasing. The conventional power plants, most generally consisting of large synchronous generators, add a considerable amount of inertia and short-circuit capacity to the grids as well as various control options. Two technologies are playing a major part in substituting the conventional power plants, namely the photovoltaics and wind turbines. Especially increased penetration of the latter is going to be considerable in Denmark. The new energy agreement, signed in March 2012 by majority of the parties in the Danish parliament, states that 50 % of the electricity supply should come from wind power in 2020 [1]. This is a part of even more ambitious plans, the vision of non-carbon society in Denmark by 2050. Consequently, the characteristics of the power system are going through a drastic transition. This obviously includes new challenges regarding matters such as grid control and stability and power quality. The new challenges call for new solutions in terms of smart grids and grid support applications.

Energy storage systems (ESSs) are among the solution that can be used for different grid support applications. A variety of ESSs, related to different properties, are available for this purpose. An overview of the available ESS technologies is shown in **Figure 1**.

Batteries [2], flywheels [3], super capacitors [4] and superconducting magnetic energy storage technologies [5] are suited for short-term grid applications. Some of the most general short-term applications are primary frequency regulation, renewable power output smoothing and inertia emulation. Previous research has indicated that primary frequency regulation (PFR) is the most profitable application on the Danish energy market [6].

The state-of-the-art batteries for short term applications have been reviewed in [7], where the Li-ion batteries are among the most promising solutions. Li-ion batteries have been under constant development for the last 20 years, where properties such as efficiency, lifetime and cost have been improved significantly. A specific methodology utilised for analysis and optimisation of the size of a battery based energy storage system for PFR is outlined in [8]. However, only in the current paper, the economical aspect of providing PFR with Li-ion battery ESS have been analysed and discussed considering different control strategies. The research is based on revenues and detailed lifetime calculations, with three different energy management strategies in the scope. Additionally, one particular solution is pointed out for investigation of the influence of new procedure in the energy management of the ESS. The analysis is based on data obtained from the Danish transmission system operator (TSO) - Energinet.dk. This includes recorded frequency profile and the relevant market data for the electrical transmission system in West-Denmark through the year 2010.

2 Li-ion battery as energy storage

There is a wide range of energy storage technologies that can be used for grid support applications. Besides the electro-chemical solutions, electromagnetic, mechanical and thermal solutions are available, each related to different operational characteristics. The classification is presented in Figure 1.

By looking at the characteristics, each storage technology appears suited for different usage and requirements. In areas such as load shifting, grid support applications and power quality, the batteries take a significant part. The attributes of using batteries can prove to be even more valuable regarding the future trends in power systems, i.e. in relation to increased penetration of renewable sources and more distributed generation [7].
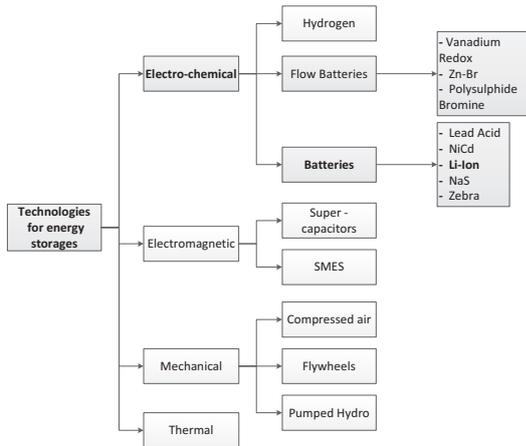

Figure 1 Classification of energy storage technologies.

A reason to work with Li-ion batteries in context of PFR service is provided by their characteristics, which include fast response, low self-discharge and long cycle and calendar life [9].

Li-ion batteries, based on LiFePO4/C chemistry, are the subject for closer examination for the considered stationary application. This chemistry is relevant since it fulfils requirements (that are specific for PFR service) regarding performance, safety and long calendar and cycle lifetime with proper thermal management [10].

3 Primary frequency regulation

Frequency deviations in a power system are caused by imbalance between generation and load. The regulation is performed by internal- or external sources. Regulation by internal source is conventionally realised by prime mover control of synchronous generators, while the external sources include technologies such as ESS and diesel generators. In the European Network of Transmission System Operators for Electricity (ENTSO-E), the frequency regulation is divided into three categories as shown in **Figure 2**, namely the primary, secondary and tertiary regulation. The PFR is based on automatic frequency measurements. The regulation must react on any deviation from the interval of 49.98 - 50.02 in 3 – 5 seconds. Furthermore, it is required that the units providing PFR to be fully activated within 30 seconds and PFR covers deviations
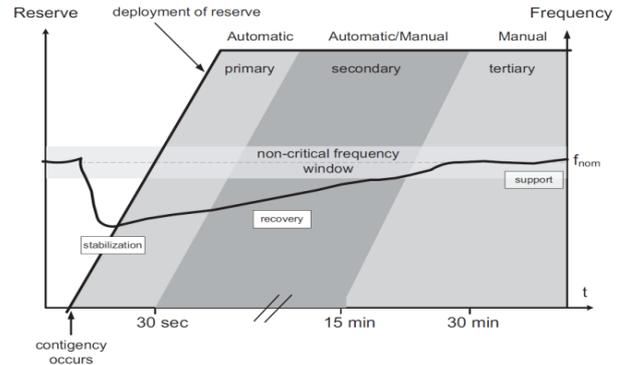

Figure 2 The ENTSOE-E requirement for frequency control reserves [13].

from the reference frequency (50.00 Hz) of ±20 mHz up to ±200 mHz. The power, either absorbed or delivered, is linearly increased from zero to maximum in relation to the deviation of 20 – 200 mHz [11].

Denmark is covered by one TSO (Energinet.dk) but divided into two regional groups (RG) and two synchronous areas of ENTSO-E. East-Denmark is a part of the RG Nordic and West-Denmark is a part of the RG Continental Europe (former UCTE). The total requirement of primary reserves in the RG Continental Europe grid is ±3000 MW [12].

The share for Energinet.dk is yearly determined by the generation in West-Denmark compared to the ENTSO-E RG Continental Europe. In 2011, the share was ±27 MW. Additionally, the TSOs can import/export primary reserves from/to the neighbouring TSOs. This agreement enables Energinet.dk to deliver up to ±90 MW of primary reserves [11].

The market for the PFR in West-Denmark is based on service bought for intervals of 4 hours. The service is sold on auctions once per day for the following 24 hours. The service distinguishes between upward- and downward regulation but both services can be covered from the same unit at the same time [11].

4 Methodology

In the following section the methodology, used for the economic analysis of providing PFR and the lifetime estimation of Lithium-ion batteries, is presented.

4.1 NPV

The net present value (NPV) expresses the worth of the investment to a specific project in terms of current wealth. The NPV can be calculated as it is shown in **Equation 1**.

$$NPV = \sum_{t=0}^{LT} \frac{CF_t}{(1-r)^t} \qquad (1)$$

where CF represents the cash flow, r represents the discount rate, and t represents the number of years in operation [14]. CF at year zero is considered as investments, and includes cost of batteries with the LiFePO4/C chemistry, which is estimated to be 2190 €/kWh and likewise are the cost of power electronics assumed to be 100 €/kW.

The cash flow for each year during operation of the ESS is based on incomes from providing services and outcomes from electric consumption (operating the batteries) taken into account. The degradation of batteries is taken in consideration in an economic model. The discount rate represents the risk of the project and the inflation, and it is assumed in this work to be 5 %. An interval of 20 years is considered for the beneficial analysis. If the Li-ion batteries reach its end-of-life (EOL) during the interval, the new investment in ESS is made. After the 20 years, the remaining value of the batteries is evaluated according to the amount of degradation and the value is added to the NPV.

4.2 Lifetime calculation

The lifetime of Li-ion batteries is an essential parameter in the analysis. It depends mainly on temperature, time, state-of-charge (SOC) and cycles. By this, two main lifetime attributes are determined - calendar life and cycle life [15]. In this investigation, it is assumed that the stationary ESS has an air conditioning system, which controls ESS temperature at 25 °C during operation. Thus, the calendar life is only dependent on the time and the SOC level. Similarly, the cycle life depends only on the cycles' depth and the SOC level. In this work the EOL criteria is considered as 20 % capacity fade [16], in which both processes contribute - calendar and cycle ageing. For the simplification, it is assumed that the capacity degradation of the Lithium-ion ESS is linear over time.
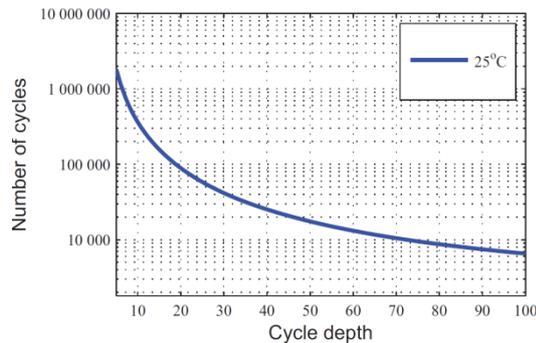
Figure 3 The LiFePO$_4$/C lifetime curve [17].

For the LiFePO$_4$/C-based Li-ion battery, the calendar lifetime and life cycles were obtained, by performing accelerated lifetime tests in the laboratory conditions. The estimated calendar lifetime is 18 years and the determined lifetime curve, based on number of cycles, is given in **Figure 3**.

Based on the SOC profile, the cycles are extracted and categorized by their depth of discharge (DOD) with 1 % resolution. **Table 1** is derived from the lifetime curve presented in Figure 3, summarizing the number of cycles for 10 % DOD intervals. The weighting factor (WF) is added to represent the respective cycles in equivalence to full DOD cycles.

A simplified cycle lifetime estimation algorithm is used for the cycle counting. DOD and number of cycles are found by using the *Rainflow Cycle Counting Algorithm* as described in [18].

| DOD [%]	WF	Cycle Life
10	0.01622	370000
20	0.06742	89000
30	0.14818	40500
40	0.23419	25600
50	0.34227	17500
60	0.46261	13000
70	0.57859	10400
80	0.69686	8600
90	0.80645	7400
100	1	6000

Table 1 Weighting factor for DOD.

5 Simulation model

The size of the ESS is arbitrary chosen to be 10 MW with a capacity of 2.5 MWh. This energy level enables the system to provide maximum power continuously for 15 minutes according to the requirements discussed in Section 3. The SOC set-point is fixed at 50 % for the comparison of the control strategies, so the ESS is equally participating in the market for upward- and downward regulation. Additionally, it is assumed that all bids are won, so maximum power is available for the services through the test period.

5.1 Model overview

The simulation model is composed of four main blocks as shown in **Figure 4**. Both the instantaneous prices and the grid frequency are taken as the input to the model. The prices are gathered from the power market data for DK-West in 2010, with one hour resolution in blocks of four hours [19]. The frequency input is based on recorded measurements in the same period with one second resolution. The control part handles the energy management strategy and the delivery of service based on the ESS SOC and the grid frequency profile. A simplified analytical model of the batteries is used, based on power and energy relationship along with the systems round trip efficiency (battery + power electronics). In the last block, the revenues are computed from won bids and processed power for charging/discharging in accordance to the price data input.
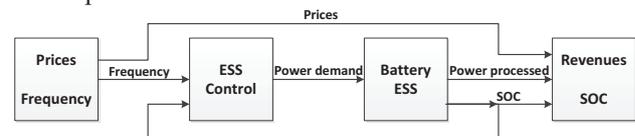
Figure 4 The scheme of the model.

5.2 Control strategies

In the present work, there are examined three control strategies, each related to a different way of energy management of the ESS. This influences the operation of the system, resulting in different usage and lifetime degradation of the batteries. Consequently, the revenues are influenced as well. The mutual SOC limits for all three control strategies are 0 % and 100 %.
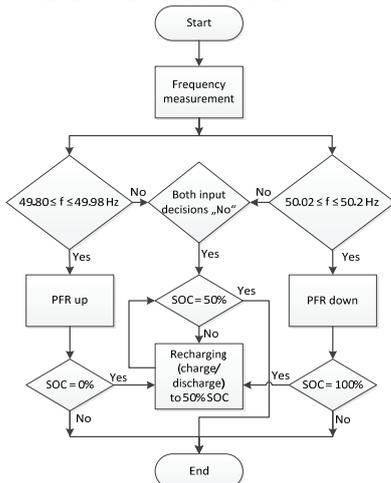
5.2.1 Control Strategy I

In the first control strategy, the control of the ESS provides the PFR service at all times requested, only with exception when the upper or the lower boundaries are reached. When the ESS reaches the limits, the PFR service is disabled and batteries are charged/discharged to the SOC set-point; whereby the PFR service is resumed. The flowchart of this control strategy is presented in **Figure 5**.
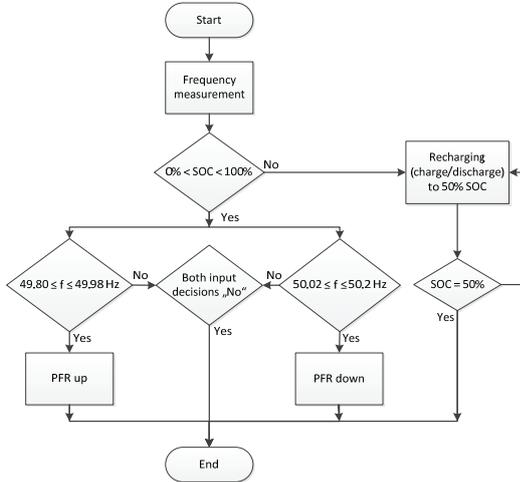
Figure 5 The schematic of Control Strategy I.

5.2.2 Control Strategy II

In the second control strategy, shown in **Figure 6**, the service is provided in a similar way as for the previous one. However, the charging/discharging is enabled to bring the ESS to the SOC set-point at every time instant, when the frequency reaches the non-critical frequency window (see Section 3). Additionally, if the service is applied continuously for a long time interval (approximately 15 minutes of full power rate), the ESS re-establishes the initial SOC when saturation is reached.
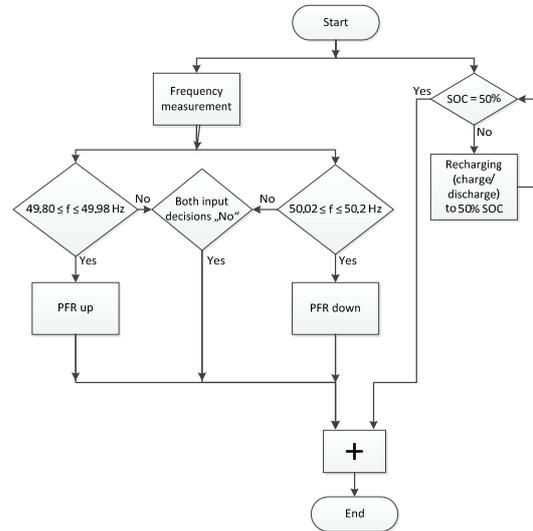

Figure 6 The schematic of Control Strategy II.

5.2.3 Control Strategy III

This control strategy, presented in **Figure 7**, is based on a power summation between charging/discharging and requested service, where both SOC re-establishing and service can be applied at the same time. The service is provided anytime as long as the capacity level of the battery is in accordance with requested power and duration. When the SOC deviates from the set point, the ESS is recharged/discharged with a lower time constant than the one applied to provide the PFR.

**Figure 7** The schematic of Control Strategy III.

6 Comparison of Control Strategies

The simulations are run for a whole year with one second resolution. The main focus is on the revenues, battery capacity fade and NPV. After one year of operation, the capacity fade and revenues are extracted and computed. Based on this information, the NPV is estimated for an interval of 20 years, as described in Section 4.1.

The comparison of results for the different control strategies is shown in **Table 2**. Control Strategy I is associated with the highest revenues in the first year. It is according to the nature of the strategy, i.e. re-establishment of the SOC only when saturation limits are reached. The rest of the time, the SOC is only influenced by the delivery of PFR. The characteristics are reflected on the depth of the cycles, as shown in **Figure 8**. In the figure, the DOD is divided into 10 % intervals based on summation of cycles with 1 % resolution. The deep cycles cause higher degradation of the batteries per year, so the revenues are lowered correspondingly in the following years. Additionally, the performance of this strategy can be questioned, when the service is requested for maximum power and the SOC is not stable at 50 %. In this case, it cannot be secured that maximum power can be delivered continuously for 15 minutes at all times.

A higher NPV is obtained when Control Strategy II is used. This strategy re-establishes the SOC after every service delivery and in that manner reduces the number of deep cycles.

The revenues (first year) are the lowest for this strategy, as more energy is bought for recharge than for the other two strategies. By applying this strategy, a further investigation is necessary regarding the influence on the grid from the fast recharging process with high power, directly after the service is provided.
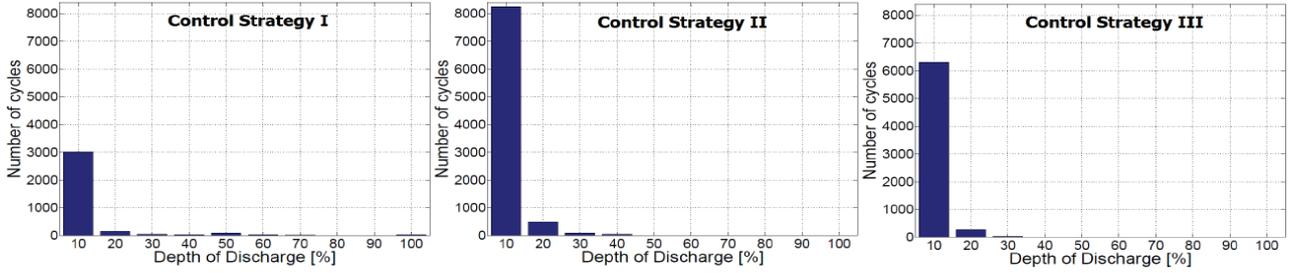
Figure 8 The cycle histograms of Control strategy I, Control strategy II and Control strategy III, respectively.

Control Strategy III gives the highest NPV and the lowest degradation in the analysis. The control is able to maintain the cycles at low DOD (see Figure 8). This strategy does not strictly provide full rate PFR as defined in Section 3. This is due to the continuous recharging, which lowers the provided power for PFR in cases where demands for service and recharging are of opposite direction in power flow. Thus, it can more be seen as a kind of inertia emulation from the ESS. Despite that Control Strategy III can be uncertain for the PFR, the performances regarding lifetime of the batteries indicate that in future, it could be a beneficial solution for other applications, such as grid stability support.

	Degradation per year [%]	Lifetime [years]	Revenues for 1st year [k€]	NPV [k€]
Strategy I	1.47	13.6	2 849	23 409
Strategy II	1.31	15.3	2 817	23 899
Strategy III	1.20	16.7	2 825	24 911

**Table 2** Results and comparison of the control strategies.

7 SOC level-based Improved Control Strategy

As observed in the previous test case, the PFR yields high benefits with all three control strategies. It has further been found, through analysis of the market data, that the average price level for PFR-upward are higher than for PFR-downward. So by raising the SOC idling point of the ESS, the revenues can potentially be increased even further. In theory, using the whole capacity of the battery for PFR-upward, i.e. with SOC set-point at 100 %, would give the highest income. However, the drawback with this option of energy management is related to the nature of the Li-ion battery technology. The degradation of Li-ion batteries increases for higher level of SOC. So it is relevant to investigate the influence of different SOC set-points on the revenues, lifetime of the batteries and NPV. Control Strategy II is chosen for this analysis, as it is considered the most suited for the delivering of the service.

7.1 Lifetime dependency on SOC levels

In this work, a linear relation is assumed to exist between capacity fade and number of cycles for the ESS. But as mentioned previously, the degradation is also dependent on the level of SOC during operation. In order to evaluate the influence from changing of the SOC set-point of the ESS, this has to be taken into consideration. The dependence of the capacity degradation of the LiFePO4/C chem-

istry on different SOC levels was not known, thus this relation was derived from [20]. In **Figure 9**, the SOC level versus the capacity factor (the rate of the capacity degradation for given SOC level) is shown (blue marks). The numerically fitted curve (red), describes the linear tendency between the SOC and the capacity factor. With background in this particular relation an expression, including the new dimension of SOC, has been derived for the lifetime computation of the batteries. The expression is shown by **Equation 2**, where C is the number of cycles, SOC_{set} is the variable set-point for the ESS and D is the capacity of the battery. D expresses the capacity in values between 0 and 1, where for example 0.8 is 20 % capacity fade.
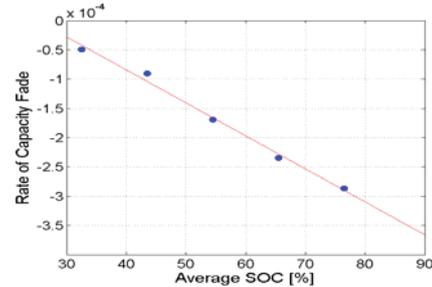
Figure 9 The rate of degradation vs. SOC average.

$$C = -\frac{1.78 \times 10^5 (D-1)}{SOC_{set} - 25} \qquad (2)$$

By using Equation 2, the coefficients are derived for each SOC_{set}. The coefficients are listed in **Table 3**. As the lifetime curve in Figure 3 is based on cycles in operation with average SOC at 50 %, this particular value is used as index number for the coefficients.

An interval with SOC set-points between 40 and 80 % is chosen for the evaluation. It is considered that the results from the accelerated ageing tests are linked to a larger degree of inaccuracy below this range. This is due to significantly increased cycle lifetime, whereby a larger error occurs in the extrapolation of the measured data. Similarly, above 80 %, is the degradation deemed too severe.

SOC [%]	40	50	60	70	80
Coefficient [-]	1.67	1.00	0.71	0.56	0.45

Table 3 List of SOC coefficients.

7.2 Results

The determined coefficients are applied to both the calendar lifetime and the life cycle curve shown in Figure 3. The coefficients are applied proportionally on each cycle life number as an approximation of the influence of SOC level on lifetime of the Li-ion batteries. How this is af-

fecting the outcome is found out by a new run of simulations, one at each SOC set-point, in the same manner as described in Section 6. The results are shown in **Table 4**. The NPV is decreasing with higher SOC set-points. This means that the influence of lifetime degradation of the Li-ion batteries on the NPV is higher than the increased benefits obtained by increasing the SOC set-point. Obviously the price level of batteries is an important aspect in this context. So the price difference between PFR-upward and PFR-downward is not the major factor, under these conditions, for the decision of improved SOC energy management. This also indicates that the optimum set-point could possibly be found in a range lower than the one investigated here.

SOC [%]	Degradation per year [%]	Lifetime [years]	Revenues for 1st year [k€]	NPV [k€]
40	0.79	25.5	2 626	25 071
50	1.31	15.3	2 817	23 899
60	1.84	10.9	3 010	22 860
70	2.33	8.58	3 203	21 653
80	2.91	6.87	3 395	19 016

Table 4 Results and comparison, at different SOC-levels.

8   Conclusion

In this paper, three different control strategies of the Li-ion based ESS for providing PFR have been analysed and compared. All three strategies were linked to high economic benefits. More accurate models of the batteries could have been used, but as all three strategies were exposed to the exact same scenario, regarding market data and frequency profile, the comparison is considered valuable. The SOC profile of the ESS is revealed to have a large influence on the outcome. An example of this can be pointed out in Table 2. Even though Control Strategy I had the highest revenues in the first year, the NPV for this strategy was the lowest. This is due to the nature of this strategy, i.e. larger degradation due to more significant DODs. Accordingly, the determined NPV for strategy II and III were higher and associated with lower DOD characteristics.

The average prices for PFR-upward service are generally higher than for the downward regulation. This means that higher income for the PFR service can be obtained, simply by bidding for more upward- than downward regulation. This entails that the SOC set-point has to be raised (originally 50 %). The drawback by doing so is a lower lifetime of the batteries, since higher SOC intervals accelerate the degradation of the Li-ion batteries. Results from prior research were used to estimate the relation between cycles and cell capacity degradation at different SOC levels for the batteries (LiFePO$_4$/C). It was found that the benefits were not increased by higher levels of SOC, as suggested. Oppositely, the benefits increased by lowering the SOC set-point. A lower price level for batteries, as well as different price relation between upward and downward regulation, could affect these results. Hence, the lifetime aspect of SOC set-point management weights more than the increased income from revenues.

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