CAUSES AND CONSEQUENCES OF BATTERIES' AGEING IN GRID INTEGRATION SCENARIOS.

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ABSTRACT

This paper presents results arising from a preliminary study preceding the demonstration work related to the IntegER project. It aims to describe how the ageing of electrochemical batteries is influenced by the operating conditions and how this ageing impact the techno-economic capabilities of the batteries all along its lifetime. The state-of-charge, the temperature, the depth-of-discharge and the cycling-rate are identified as the main influencing factors of ageing. Ageing cause both a capacity fade and a power capability loss. Only the capacity fade has a noticeable impact on the economic benefits of batteries. Simulations of practical cases using recently published analytical model of ageing have been done. It highlights that unexpected operational failures might happen if ageing is not considered while batteries are sized. Otherwise, it is shown that for a given service, the lifetime, and therefore the total benefits, of batteries of different sizes is approximately the same. Finally, the impact of ageing on economic benefits is shown to be minimal in grid upgrade deferral scenarios.

INTRODUCTION

The IntegER research project was launched by SINTEF Energy Research together with the Norwegian utilities in 2017, to build knowledge about grid and market development possibilities arising from the integration of energy storage within the Norwegian distribution grid where the main storage technology is hydropower. Battery energy storage systems (BESS) are promising solutions to support the transition of electricity grids to more flexible networks suitable for the large-scale integration of distributed energy sources. Understanding how electrochemical batteries behave and age is one of the key factors for the optimal planning of the network's development. This paper is addressing the techno-economic losses due to the BESS ageing, answering to the questions: How do electrochemical batteries age under grid utilization? What are the effects of ageing on the techno-economic benefits of the battery integration in distribution networks?

After this introduction, a first section is dedicated to the review of the theorical causes and consequences of battery's ageing. Then the authors present their methodology for this work, before describing the different cases that have been simulated and finally present and comment the results.

THEORY

The ageing of electrochemical batteries has been widely researched by material scientists. Since this study focus on the bilateral relationship between the way the battery is operated and its ageing, this section focuses on the main principles of battery ageing how ageing is affected by operating conditions and affect the capabilities of batteries. The reader is referred to the quoted references and the related literature for more material-oriented explanations. Battery ageing refers to the depletion of the battery's performances: capacity and power capability. Ageing happens no matter how the battery is used. This means even though the battery is not cycled it loses energy. This is referred as calendar ageing. However, the ageing is also influenced, generally enhanced, by cycling. One talks of cycling-related ageing. The more a battery age, the more it gets closer of its end of life. For electrochemical battery the "End of Life" (EOL) criterion is typically defined as the moment when the battery has lost 20% of its initial capacity.

Consequences of ageing

The three direct effects of battery ageing are: capacity fade, power capability loss and battery failure. Performance depletion results from alterations of the charge carrying process. Those alterations might concern the charge carriers themselves or the other active materials involved in the migration.

Capacity fade

Capacity fade refers to a loss in the active material and charge carrier inventories. Charge carrier can become unavailable either by being consumed (i.e. modified) within parasite reactions, or isolated from the other reactors (for instance, because of internal fragmentation).

Power capability loss

The power capability (i.e. the maximum power at which the battery can operate) is directly related to the cell internal resistance. If the internal resistance increase, the thermal losses do so, and the electrical power available at the battery terminal decrease.

Battery failure

The cell's failure is caused either by an internal short circuit resulting from the puncturing of the separator, by a thermal runaway, or by a rise of the internal pressure.

Influencing factors

Ageing is influenced by environmental and operating factors. The temperature and the SOC of the battery influence both calendar and cycling-related ageing processes. Cycling-related ones are also influenced by the depth-of-discharge (DOD) and the cycling rate (C-rate).

Cyclic ageing is influenced by temperatures, state of charge, depth of discharge and operating current, while calendar ageing is mainly dependant of temperature, state of charge and time [1].

Effects of the temperature

Temperature is known to catalyse electrochemical reactions. In batteries, it affects both safety, performances and cycle life [2] Ageing is enhanced at high and low temperatures. For Li-ion batteries the ideal working range between 10°C and 60°C [1]. Air conditioning systems can be used to keep the battery in this temperature range.

Effects of the state of charge

In lithium batteries, a high SOC involves a high potential disequilibrium at the anode/electrolyte interface [1], [3] and promotes all the mechanisms depicted in Figure 1. At low SOC, the cell voltage is reduced. It favours the decomposition of the active material and the corrosion the current collectors [3].

Effects of the cycling conditions

The cycling of a cell is characterized by the (dis)charge rate and depth of the cycle (i.e. the difference between the maximum and minimum SOC of the cycle), DOD. Both characteristic influence the cell's ageing process. The DOD is an important factor of degradations in Li-ion batteries [3]. The increase of the DOD causes a loss of power capability.

C-rate characterizes how fast the battery is charged and discharged. High c-rate tends to emphasize the influence of the other factors. Indeed, the related high current (compared to the cell capacity) induce an internal temperature rise and amplify the cell's polarization and imbalance, what favours degradations [3]. C-rate effect must be especially considered in fast-charging application that are characterized by high power and subsequently high cycling rate. According to laboratory tests, in other grid applications, the c-rate effect is small because grid-scale batteries are usually scaled to operate at less than 1/3C (i.e. they cannot be fully discharge within less than 3 hours) [4].

Main ageing mechanisms

Since the lithium-ion is an expensive, but very promising technology for various kinds of services, the ageing mechanisms of those batteries are continuously investigated by the scientific community. The literature provides good understanding of most of the mechanisms involved in the ageing process. Ageing of Li-ion batteries is caused by multiple and interdependent processes [1]. Electrochemical degradation mechanisms occur in every part of the battery and mostly at the different interfaces [3]. Degradations have more impact by the anode side than by the cathode sides. The more remarkable degradation mechanisms are listed below. Figure 1 illustrates the ageing mechanisms taking place by the anode side.

Solid Electrolyte Interphases growth

The Solid Electrolyte Interphase (SEI) is a passive layer at the anode/electrolyte interface. It results from reactions between the electrolyte and the active material of the anode. Although it ensures the cell's stability, its growth consumes active material and causes an increase of the internal resistance. Therefore, SEI growth results in capacity and power capability fade [2]. This is the main ageing process in Li-ion batteries. This mechanism is mainly enhanced by high SOC and high temperatures.

Mechanical stresses

Internal pressure variations are caused by Li ions insertion/extraction in the electrodes and all structural change in the cell's materials. It mainly happens while the battery is cycled. It results in cracks, active material insulation and loss of contact between particles. In particular, by the anode side it induces graphite exfoliation and gas formation.

Dendrite growth

At high SOC [3] and low temperature [1] lithium metal may precipitate at the anode surface. This results in loss in cyclable lithium inventory and the growth of dendrite that may puncture the separator and cause fatal short-circuit. Dendrites are also created by dissolved particle of the cathode that migrated to the anode side.

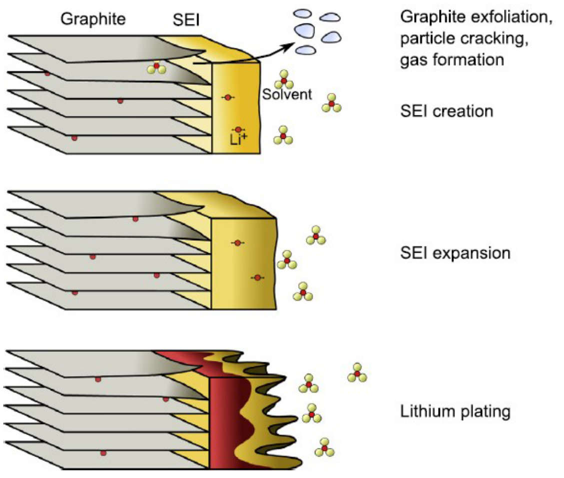

Figure 1: Ageing effects on Li-ion battery negative electrode [2]

AGEING MODELLING

Modelling the ageing of electrochemical batteries is a central issue of grid development planning and operational research aiming to optimize the use of batteries as a storage solution for any usage. Following paragraphs gives a short overview of the state-of-the-art of batteries' ageing models and summarises the modelling choices made for this study.

State-of-the art overview

The literature describes three main modelling approaches. Each has its own pros and cons.

Physically-based models are the most faithful to the electrochemical mechanisms. They are based on the constitutive laws of the battery's internal mechanisms. Those laws are mainly described by partial differential equations. Solving them regarding a set of conditions gives reliable results about the cells' performances and ageing. However, such models are very computationally expensive. This makes them hardly usable in operational simulation and optimisation framework.

In the contrary, empirical models are computationally efficient but perform poorly in terms of accuracy when simulated cases differ from the conditions the models are tuned on. Therefore, empirical models are hardly adaptable to a wide set of operating conditions.

Finally, semi-empirical models consist in using reasonable approximations and analytical solutions of the constitutive laws of the physical mechanisms. Their main interest is to improve the processing time of the physically-based models while keeping an approach allowing to distinguish the effect of the different parameters or processes from each other. This makes them globally more reliable and adaptable than empirical ones.

Modelling choices

Capacity fade model

This study uses the "Physically-based reduced order" model described by Jin et al. in [5] to simulate the capacity fade. It considers all the important factors influencing the capacity fade (temperature, SOC and c-rate) and model both calendar and cycling-related ageing. This choice has been motivated by the relatively good computational efficiency and reliability of this model. According to [5], it is slightly less accurate than the typical electrochemical models, but it is 2400 times faster. Furthermore, it put down root into widely accepted constitutive laws and does not include any ad-hoc term. The overall formulation of the model is given and described below.

$$Q_{loss} = Q_{cal} + Q_{cyc} \quad (1)$$

$$Q_{cal} = \int_0^t \frac{k_{cal} \cdot \exp\left(-\frac{E_{cal}}{R \cdot T}\right)}{2(1+\lambda\theta)\sqrt{t}} dt \quad (2)$$

$$Q_{cyc} = \int_0^t k_{cyc} \cdot \exp\left(-\frac{E_{cyc}}{R \cdot T}\right) \cdot SOC \cdot |I| \, dt \quad (3)$$

Q_{cal} and Q_{cyc} respectively represent the capacity fade due to calendar and cycling-related ageing during over a time period. k_{cal}, k_{cyc}, E_{cal}, E_{cyc} and λ are fitting factors which are tuned on experimental data. θ model the kinetic of side reaction related to the SEI growth and depends on the SOC and the current which is proportional to the c-rate.

Power capability loss model

To model the power capability loss due to the ageing of the battery the authors use an empirical model derived from accelerated ageing tests performed in laboratory. It is described by Stroe in [6]. Such as the capacity fade model, it distinguishes the calendar losses, PC_{cal}, and the cycling-related ones, PC_{cyc}. The formulation of the model is given below. The cycling-related loss model takes both the DOD and the number of cycles, N_c, as parameters, while the calendar one considers only the influence of the SOC. $\{p_1, ... p_4\}$ are fitted parameters tuned on experimental data.

$$PC_{cal} = p_1 \cdot SOC^{p_2} \cdot t \quad (4)$$

$$PC_{cyc} = p_3 \cdot DOD^{p_4} \cdot N_c \quad (5)$$

METHODOLOGY

Simulation approaches

The overall purpose of this study consists in both understanding the causal links between the operating conditions and the ageing of the battery and observing the impacts of battery degradations when BESS are integrated to the distribution grid. This is done

Two different simulation approach are chosen regarding the objective. The first one consists in running the ageing models over the full simulation horizon at once. This is used to observe the degradation responses to different shapes of profile in order to identify the main causal relationship between operations and degradations. The second one is used to monitor the ageing over various simulation of long-term scenarios. This is a simulation and optimization friendly approach. The ageing is computed at each step of the simulation instead of waiting to know the full operation profile. It allows the ageing to be a decision factor.

Practical cases

Practical cases are simulated in order to evaluate the techno-economic impact of ageing. In those cases, batteries are used to achieve load-peak shaving in an end-user demand shifting case and in a grid upgrade deferral case. The benefits of demand shifting correspond to the savings done by buying energy when demand (and thus price) is low instead of during high demand periods. In grid upgrade scenarios the storage capacity of batteries is used to absorb and supply the production and load surplus that cannot be managed by the grid because of the limited carrying capacity of the grid.

SIMULATIONS AND RESULTS

Influence of operating condition on the battery's ageing

To illustrate and identify the impact of the different influencing factors the models have been run under various conditions. In each simulation the power capability loss over the battery lifetime was around 2%. The following paragraphs focuses on the capacity fade.

Capacity fade under idle conditions

Calendar ageing is influenced by the temperature and the SOC of the battery. Figure 2 illustrates how a battery ages during one hour under various idle conditions (i.e. when it is not cycled). It clearly highlights that high SOC and high temperatures are the worst conditions to store energy. This is in agreement with the theory.

Impact of DOD on the capacity fade

As shown in Figure 3, the cycle life (i.e the number of cycles operated before reaching the EOL criterion) appears to decrease proportionally to the inverse of squared-root of the DOD. This can be explained by the fact that the highest the DOD, the more the charge meet severe SOC conditions.

Impact of c-rate on the capacity fade

The c-rate characterizes how fast the battery is cycled. Generally, grid-scale batteries are operated at less than 1/3C. High c-rates are known to enhance the battery ageing. This is confirmed by the simulation results plotted in Figure 4 which show that the battery lifetime decreases as the c-rate rises. However, the results also highlight that the cycle life rises with the c-rate. It can partly be explained by the fact the duration of a cycle is lower at high C-rate.

Techno-economic impact of the battery's ageing

Technical failure due to ageing

In the first simulation a 1.2kWh battery is used to shave 30% of the load of one house. The battery's capacity has been chosen to meet the technical requirements of the operation without considering the capacity fade due to ageing. The simulation results plotted in Figure 5 show that shaving failures appear after the fifth year. That means that the battery is not physically able to inject as much energy as it should. The load is then supplied by the grid. This is a direct consequence of the ageing of the battery. Therefore, it is important to consider it while sizing the battery in order to ensure that the planned services are supplied during its whole lifetime.

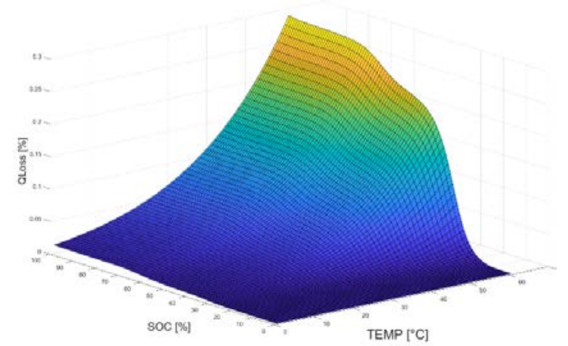

Figure 2: Capacity fade during one hour under idle conditiions

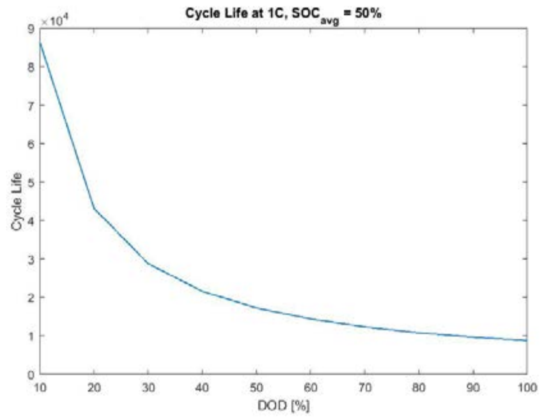

Figure 3: Cell's cycle life versus DOD

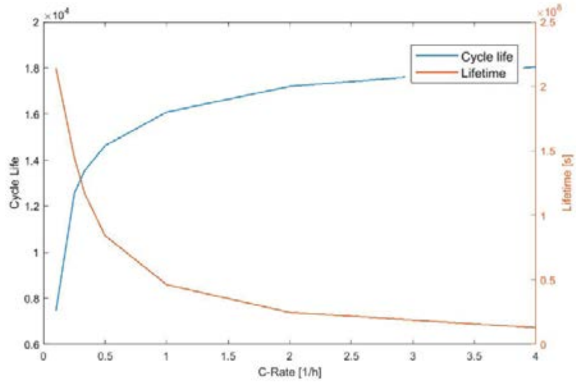

Figure 4: Cell's cycle life versus the c-rate, DOD = 40%, SOC $_{avg}$ = 70%

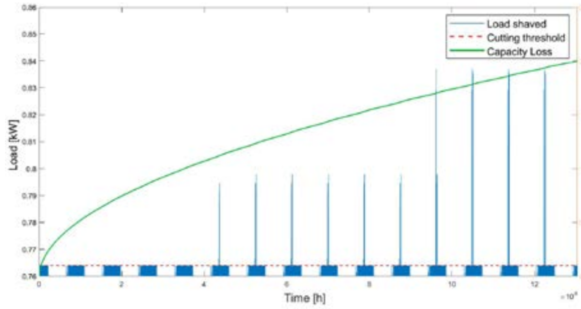

Figure 5: Example of shaving failure due to ageing

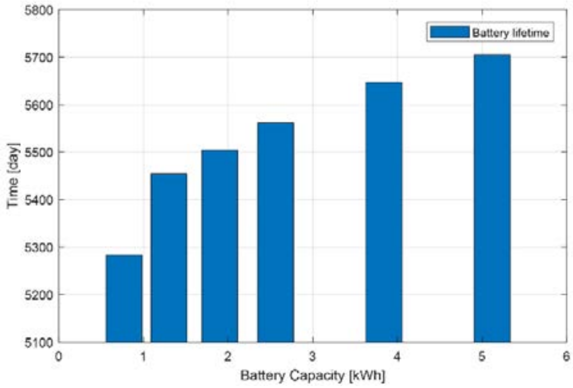

Figure 6: Lifetime of batteries versus their capacity

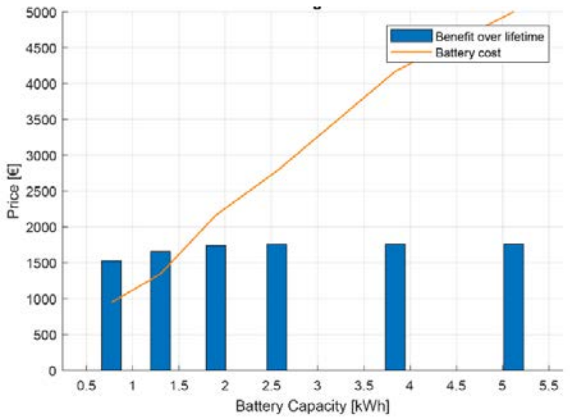

Figure 7: Benefit of demand shifting, regarding the capacity

Demand shifting scenario

Figure 6 and Figure 7 show the result of simulations in which batteries of different sizes are used to achieve the shifting of 30% of the demand of one house. Battery lifetime rises with the battery capacity. There is a difference of 421 days between the lifetimes of the smallest and the biggest battery. However, the total benefits do not rise much with the battery size while the battery cost keep rising. That can be explained by the fact that the shaving objective is the same for the different batteries. Therefore, the lifetime is the only difference between the capabilities of the different batteries. This simulation highlights that it can be more valuable to do demand-shifting at a neighbourhood scale to amortize the cost of the battery.

Grid upgrade deferral scenario

In grid upgrade deferral scenarios, the benefit of one year of deferral corresponds to the cost of the upgrade in proportion to the utility charge rate minus the cost of the battery. In such case the impact of the ageing could be noticeable if it was limiting the capabilities of the BESS such as the investment could not be covered within the expected deferral period. This would mean that the battery is as expensive as the upgrade itself. Then, it would be useless. Furthermore, simulations show that in every scenario the battery lasts more than 13 years. Therefore, its ageing does not influence the rentability of the upgrade deferral.

CONCLUSION

The ageing of electrochemical batteries is caused by multiple and interdependent parameters. It is mainly influenced by the temperature and the operating conditions (SOC, DOD and c-rate) and enhanced when those parameters are high. In typical distribution grid scenarios, BESS operate at 1/3C or less. In such conditions, ageing is mainly caused by calendar mechanisms and the average battery lifetime is around 15 years. Nonetheless, the simulations have shown that it is important to consider while planning grid development and operations in order to track the capabilities of the battery over its lifetime and optimize its utilisation. The main consequence of the ageing is the capacity fade. Ageing also causes a power capability loss. In average a battery loses less than 2% of power capability over its lifetime. It does not have a big impact on the techno-economic benefits of a BESS. At an end-user scale the economic benefits of BESS are limited. Since the related investment cost is significative, and the battery lifetime limited, it is not valuable to oversize it. At a distribution grid scale, the cost of a battery is small compared to the upgrade costs. Then, the economic impact of ageing is limited.

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