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# Ageing inhomogeneity of long-term used BEV-batteries and their reusability for 2$^{nd}$-life applications

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## Abstract

In this paper li-ion battery modules, which have been used in a battery electric vehicle (BEV) for several years and for up to 50,000 miles, have been investigated due to reusability in a 2$^{nd}$-life application. The aim was to choose modules with a similar state of health (SOH) and remaining useful life and to reassemble them to get an affordable battery pack for a stationary storage system.

All in all 104 modules have been quick-tested. Since the modules show similar characteristics and in order to estimate the dispersion of the capacity and the ohmic resistance between the modules, 10 of these modules have been investigated in detail. Furthermore one module has been disassembled and the single cells have been measured to estimate the inhomogeneity on cell-level. 70 modules showing similar SOH have been put together in a battery pack, which has been integrated into the "Efficiency House Plus" in Berlin. This project demonstrates a possible 2$^{nd}$- life application of aged BEV-battery modules.

On the one hand, the testing of the used modules needed a lot of time and testing capacity. On the other hand the testing results show limited validity, because they are just a snap-shot of the current attributes of each module but do not consider its history. So it is hard to determine the actual SOH and nearly impossible to estimate the remaining useful life of a used li-ion battery module without knowing its complete history, especially because of the non-linear aging characteristics of li-ion batteries. To provide a cost-efficient and automatic evaluation of the battery aging, this paper suggests a server based battery management system (BMS), which logs all relevant cell data and creates the history of each module. Thus more reliable conclusions about the remaining useful life and the actual value can be drawn and different options for servicing, repair and reuse arise.

*Keywords: Battery aging, inhomogeneity, li ion battery, 2$^{nd}$-life, server-based battery management system*

## 1 Introduction

For a battery electric vehicle (BEV) mainly li-ion batteries are used for storing energy. Already a decade ago optimistic estimations predicted the price development of li-ion battery packs for electric vehicles to go down to 250 $/kWh [1]. This goal is nearly reached nowadays and smoothed the way for the commercial launch of electric vehicles. Nevertheless the battery stays the

most expensive part of a BEV. Therefore a minimum lifetime of 10 years is demanded by the user. Even after this period or when the battery cannot fulfill the BEV-requirements anymore, it might be valuable in other applications e.g. stationary storages for renewable energy. So selling the aged BEV-battery to a 2nd-life user could reduce the costs for the owner of a BEV. Therefore a reliable determination of the actual SOH and especially of the remaining useful lives of the aged BEV-battery modules is necessary.
Without knowing the history of each module this is nearly impossible, because of the highly non-linear aging phenomena, which depends on various influences, e.g. temperature [2],[3]. In Fig. 1 the ageing behavior of an 18650 cell is shown. The degradation of the useable capacity is linear until a certain point is reached.

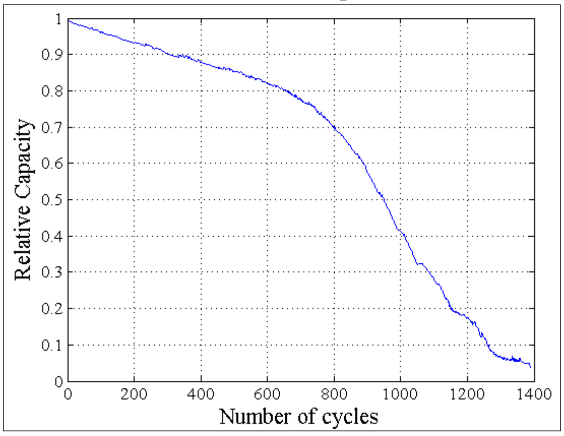


Fig. 1: Non-linear ageing behavior of a 18650 cell

In addition the technology of li-ion batteries advances very fast. Because of this there is only little time to gather detailed knowledge about the specific aging behavior of a certain type of cell by applying long-term tests.

The aim of the presented work was to validate used BEV-modules, which have been used in a battery electric vehicle (BEV) for more than 3 years and for up to 50,000 miles, and to group the modules with similar characteristics in order to get a homogenous battery pack for a stationary storage application.
Hereby one focus of this paper was to investigate ageing inhomogeneity of battery modules in BEVs. Therefore 104 BEV-modules have been quick tested. Since the characteristics between the modules do not vary too much, 10 modules have been investigated in detail. With this analysis the inhomogeneity on module-level can be estimated. To also estimate the inhomogeneity on cell-level one of the aged BEV-modules has been disassembled and investigated.
Those modules showing similar characteristics have been put together in a battery pack, which has been integrated into the "Efficiency House Plus" in Berlin for storing fluctuating renewable energy.

The measurements presented in this paper, show that it is nearly impossible to predict the remaining useful live of a used BEV-module without knowing its history. That is, because the properties of the modules do not vary very much for a large part of their lifetime. Thus the remaining useful live cannot be determined by a snap-shot measurement without knowing the history of each module. To get the whole module history a server-based BMS with a dual estimation procedure of the SOC on board the BEV and the SOH on the server is suggested in this paper. The crucial point is to gather detailed knowledge of each battery module including its complete history and its actual state. Based on this the remaining useful life can be determined and cost-saving strategies for servicing, repair and reuse arise.

## 2 Inhomogeneity between BEV-modules due to aging

Two different battery packs from an BEV-prototype fleet have been investigated to evaluate the actual SOH and their remaining useful capacity. All in all 104 BEV-battery modules have been quick-tested. The nominal capacity of a module is 103,4 Ah. Because the quick tests revealed no big deviation in the voltage characteristic curves, 10 modules have been tested in detail. The results are shown in Fig.2.

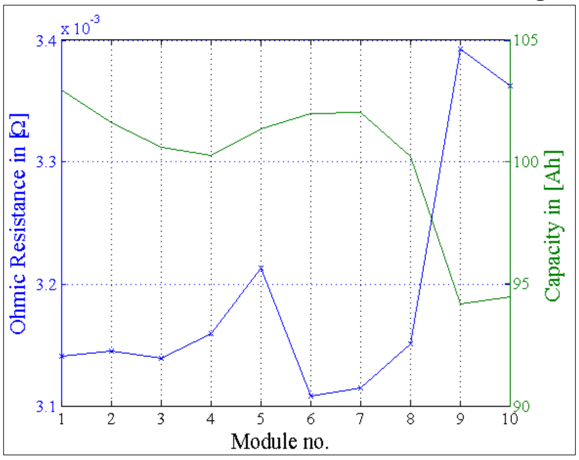


Fig. 2: Comparison of 10 BEV-modules (no. 9 and 10 have been used almost one year longer in a BEV)

Modules 1 to 8 and modules 9 and 10 have been used in one BEV each. The first 8 modules have been used for more than 3 years and the other 2 modules have been used for almost 4 years. Modules 1-8 have still nearly nominal capacity. Modules 9 and 10 show a more significant loss of capacity, but also hold more than 90 % of the nominal capacity. Although we do not know, what capacity the modules had at the beginning of their BEV-lives, after more than 4 years in use there was no imperative to remove one of the 104 tested modules from the BEV.
The ohmic resistance of a new module should be less than 3.0 mΩ. The measurements of the 8 less stressed modules show, that the ohmic resistance increased by less than 5 %. The 2 modules, which have been used for 4 years, show a little bigger increase (< 13 %) in the ohmic resistance.

Further studies will show how the operation in the "Efficiency House Plus" will influence the aging of the different modules.

# 3 Aging inhomogeneity of cells in battery modules

One of the BEV-modules has been disassembled to test each specific cell in terms of inhomogeneity due to aging on cell-level. Of course all examined 18650 cells were of the same type. 25 brand-new cells were tested to get a reference (New). 24 of the investigated cells have been connected in parallel in the BEV-pack (Set1). Furthermore 23 cells from the same BEV-pack, which also have been connected in parallel but on a different voltage level have been investigated (Set2). The cells from Set1 and Set2 were connected in series in the same BEV. Therefore they have experienced the same load profiles.

To determine the capacities a standardized discharge test has been applied on each cell [4], [5]. The box plot in Fig. 3 shows the measured capacities and their dispersion. It shows very clearly that the capacity decreases depending on the age of the cells. The loss in capacity is in the range of 1 %, which is similar to the results on module-level shown in chapter 2. Nevertheless Set1 and Set2, show a lower dispersion than the brand-new cells. The maximum difference between the new cells is 77,3 mAh, whereas the cells of Set1 only differ by 54,2 mAh.

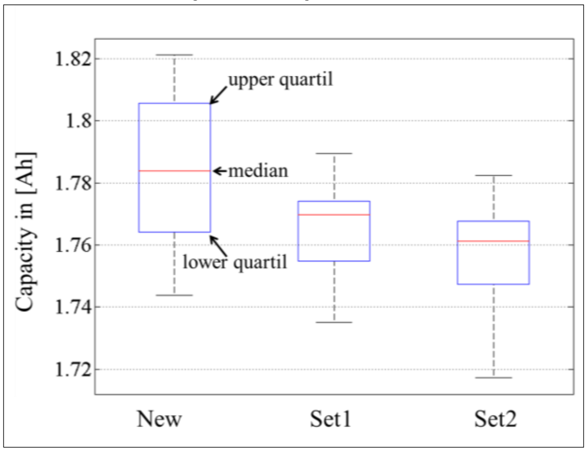


Fig. 3: Measured capacities and dispersion

Additionally the ohmic internal resistance of each cell has been measured (see Fig. 4). Equivalent to the results on module-level aging is apparent due to the increasing internal ohmic resistances of the used BEV-cells. But also here the dispersion is higher within the new cells than within the sets of aged cells.

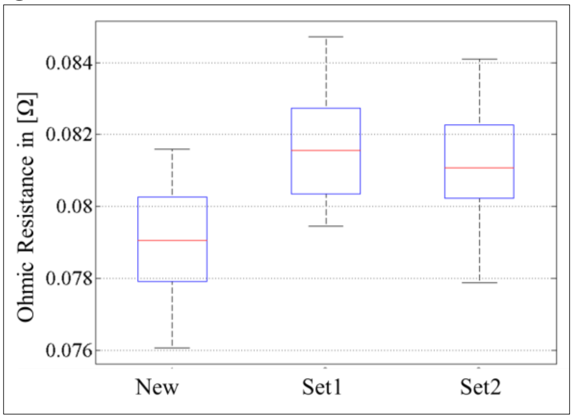


Fig. 4: Ohmic internal resistance and dispersion

Finally an electrochemical impedance spectroscopy (EIS) has been carried out with every cell. Every cell has been charged up to a state of charge (SOC) of 50 % of its actual available capacity.
The starting frequency of the EIS was 10 kHz and frequency decreased down to 10 mHz, because no aging effects were observed at higher or lower frequencies. The results of the EIS are shown in Fig. 5. The bold lines mark the boundaries within which the other curves of the same set of cells are located.

The EIS shows very clearly that ageing has an impact on the ohmic internal resistance and on the charge transfer reactions of the cell.

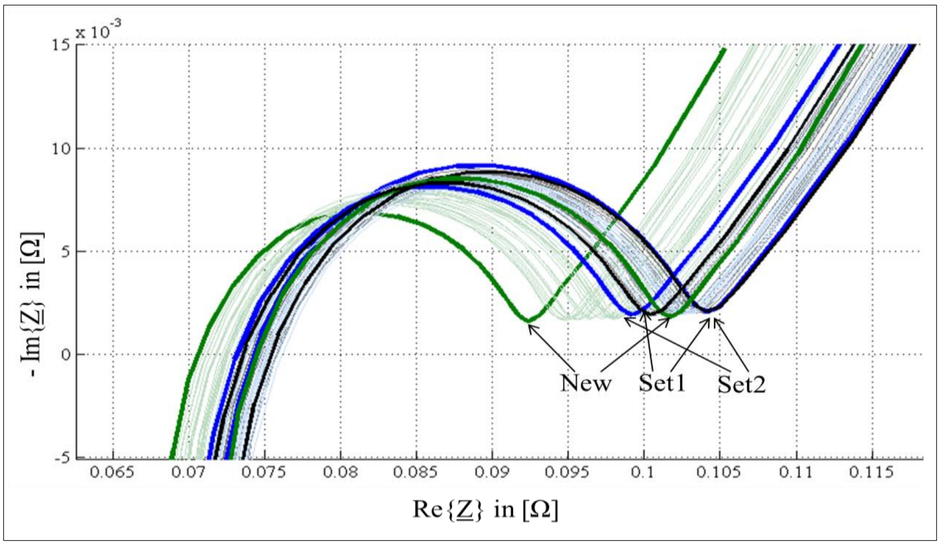


Fig. 5: EIS carried out on the single cells of a module to visualize ageing effects

While the dispersion of the used BEV-cells is spreading less than 4 mΩ, the new cells vary significantly more. Especially at the frequencies belonging to the charge transfer the difference in the impedance is more than 10 mΩ for the new cells.

There can be two reasons for the observed effect, that the new cells show a greater dispersion than the aged cells:

1. The BEV-cells have been selected very carefully before pack assembling or/and are different from those freely available cells.
2. Aging effects depend particularly on the voltage of the cells. The cells in parallel always had the same voltage and what is more, the parallel cells could adjust their SOHs because of stray electric current.

Since there is no official literature, in which this effect has been described, further investigations have to be and will be done on this field of research.

# 4 2nd-life application of aged BEV-battery modules in the "Efficiency House Plus"

When BEV-battery modules do not fulfill the performance requirements of the BEV-application anymore, the modules usually have still enough capacity for fulfilling the requirements of a more moderate application. To practically demonstrate a 2nd-life usage, the 70 most similar modules from the 104 tested modules were chosen and reconfigured to a battery pack, for storing renewable energy in the "Efficiency House Plus". This project was initialized by the German Federal Ministry of Transport, Building and Urban Development to demonstrate the potential in domestic energy savings. The technologies that are integrated in the "Efficiency House Plus" provide in summary a positive energy balance. That means the house generates more energy from renewable energy sources, e.g. its solar panels, than its inhabitants consume. With the surplus energy electric vehicles like a scooter or a BEV can be recharged at the "Efficiency House Plus" via an induction charge system.

The fluctuating energy will be buffered in the 2nd-life battery pack, which can store up to 43 kWh. The power requirements of the complete system are set to 6,5 kW. The maximum power does not exceed 7,2 kW over five minutes of discharging time. Fig. 6 shows the CAD design of the realized 2nd-life battery pack.

Fig. 6: CAD design of the 2nd-life battery pack

The battery pack has already been build up and integrated in the “Efficiency House Plus” in Berlin.

# 5 Prospect

In the previous chapters, the testing of BEV-modules and the inhomogeneity on module- and cell-level have been described. From theses 104 modules the 70 most similar modules have been reconfigured to a 2nd-life battery pack. By experiencing the whole process, from validation of the used BEV-modules to integrating them into a 2nd-life application, some significant conclusions can be drawn:

1. The tests are very time and cost intensive
2. It is nearly impossible to determine the remaining useful life of a module without knowing its history. Even if the tests are more sophisticated merely a snap-shot of the actual state of each module can be received. The non-linear aging characteristics make this even more difficult, because one never knows, when the capacity will start to decline much faster.
3. The low degradation and dispersion of important module parameters due to ageing exceed the expectations. So the modules can be reused in 2nd-life applications.
4. As demonstrated with the “Efficiency House Plus” there is a significant potential in 2nd- life usage.

So the main problem that has to be solved is to record the history of the BEV-modules. This can be done by a sophisticated BMS, which is acquiring the data of the battery pack. This data has to be processed to estimate certain battery states like the actual SOC and SOH. Since the SOC is changing much faster than the SOH a dual estimation procedure based on Extended Kalman Filter (EKF) is applied. Fig. 7 shows the structure of the dual estimation procedure. [6],[7]

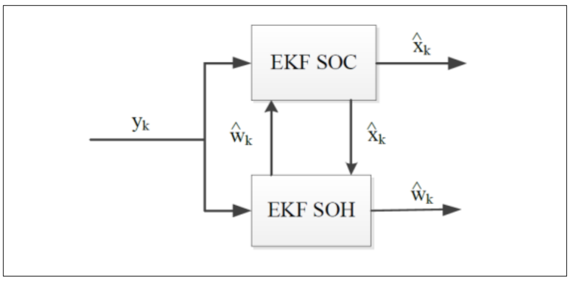


Fig. 7: Dual estimation procedure based on EKF

In this figure $\hat{x}_k$ is the state-vector, which contains all variables for estimating the SOC. The vector $\widehat{w}_k$ is for the parameters of the li-ion battery model, which is the basis for both EKFs. The characteristic of the parameters will change slowly due to ageing, so this is the EKF for estimating the SOH.

Based on a modular BMS, mainly designed as a development environment for research applications, various SOC and SOH algorithms were implemented. The applied BMS consists of a master-slave topology where every slave measures cell parameters and calculates the relevant data of 12 cells. Because every slave module hosts his own processing unit, consisting of a 32 Bit and 80 MHz controller, the entire system can be extended very easily.

The investigation of the SOC and SOH determination reveal, that even with a 32 Bit core processing unit, the used battery model has to be simplified due to calculating capacity. Because the accuracy of the estimated states is important and the data volume for logging the complete history is too high for an on-board system, the complex calculations and the comprehensive data acquisition should be outsourced to a central server as far as possible. Still the EKF for the SOC estimation has to be implemented on board the BEV, but the SOH estimation can also be done on the server, because it is not changing very fast and has not to be updated even every day. The central server can also log the complete history of each module easily. Furthermore by implementing a central server, the ageing characteristics of different battery packs in different BEVs can be compared. Therewith the ageing phenomena of the specific li-ion technology can be learned. This is a big advantage, because the li-ion technology advances very fast and there is not enough time for long-term testing. This method has high potential to observe the real ageing behavior and to estimate the remaining useful live very precisely.

On the one hand the costs for the BMS can be reduced with this server-based structure and on the other hand the gained knowledge enables different options for servicing, repairing and reusing the battery modules. In Fig. 8 some possibilities are shown.

The BMS is rigidly coupled to the corresponding module and logs the cell data over its entire lifetime. At the beginning after the assembly of the module the BMS calculates all cell parameters. Tolerances between the battery modules due to cell manufacturing cause different qualities of cells. The quality of the cells determines its application environment. High quality cells commonly are used in a BEV whereas B-quality cells could be used in stationary energy storage systems as shown in section 4.

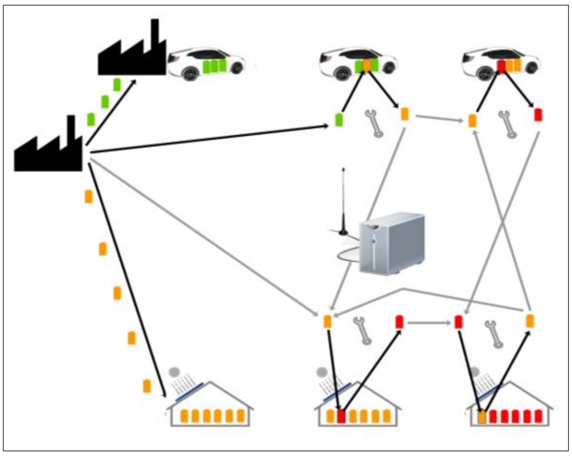

Fig. 8: Possibilities for servicing, repair and reuse

The server based data logging system allows comparing the aged modules and helps to learn about the ageing behavior of the modules in their single application. If a single module of a BEV-battery pack degraded faster than the rest, the module would limit the performance of the whole battery pack. This situation would be detected and the affected module can be replaced by a newer one in order to retain a homogenous battery pack in the BEV. Now the removed battery module can be used as a 2$^{nd}$-life module in other applications.

# 6 Conclusion

In the presented work testing results of BEV-modules and their inhomogeneity on module- and cell-level have been described. This is one of the first official investigations, where 3 respectively 4 years old battery modules from a real BEV have been available. Because the quick test of 104 modules showed no significant variation of the voltage characteristics, 10 modules have been investigated in detail. The capacity loss of the battery modules even after 4 years of usage in a BEV is below 10 %. To get information about the inhomogeneity on cell-level one module has been disassembled and the single cells have been measured and compared with brand-new cells. Additionally an EIS has been made for every single cell, and shown, that the parameters of the brand-new cells differ more than those of the aged cells. One reason therefore could be, that only very similar cells have been chosen for a module. Another possibility is, that the parameters of the cells adjusted themselves, because they were connected in parallel.
From the 104 quick-tested modules the 70 most similar modules have been reconfigured to a 2$^{nd}$-life-battery pack for the “Efficiency House Plus” in Berlin.

By experiencing the whole process chain, from validation of the used BEV-modules to integrating them into a 2$^{nd}$-life application, some significant conclusions can be drawn:

1. The tests are very time and cost intensive
2. It is nearly impossible to determine the remaining useful life of a module without knowing its history. Even if the tests are more sophisticated merely a snap-shot of the actual state of each module can be received. The non-linear aging characteristics make this even more difficult, because one never knows, when the capacity starts to decline much faster.
3. The low degradation and dispersion of important module parameters due to ageing exceed all expectations. So the modules can be reused in 2$^{nd}$-life applications.
4. As demonstrated with the “Efficiency House Plus” there is a significant potential in 2$^{nd}$- life usage.

For reusing and validation of aged BEV-battery modules the history of each module is of great importance. In this paper a dual estimation procedure based on the EKF is presented. With this the SOC can be estimated with the BMS on-board the BEV and the SOH can be implemented on a central server. This central server can help reduce the costs of the BMS and can be used for storing the module history.
Based on the accurate estimation of the remaining useful life of a BEV-module, different options for servicing, repairing and reuse arise. By selling and reusing the aged BEV-modules the costs for the BEV could be significantly reduced. Furthermore the 2$^{nd}$-life battery packs could help store renewable energy and stabilizing the electric grid.

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