Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
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doi: 10.3850/978-981-18-8071-1_P258-cd

Challenges in the Real-World Evaluation of Traction Batteries at the End of their First Life

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Lithium-ion batteries are the most used cell technology in electric vehicles in recent years and today. Forecasts show a global supply of more than 200 GWh/y in 2030 of batteries available for reuse in second life applications. Determination of the overall status and explicitly the state of health is a difficult task, especially for municipal recycling facilities confronted with scarce information about the history and construction of the traction batteries. The frequently used technical approaches require a dismantling of the battery pack down to the cell level for an accurate condition assessment. However, for security reasons, a quick and accurate assessment is required at the pack or module level. This paper provides an overview of possible approaches to the assessment of used battery packs from receipt at the recycling facility to various measurements of the state of health determination with regard to the time required.

Keywords: lithium-ion batteries, energy storage, circular economy, electric vehicle, state of health, battery testing.

1. Introduction

Lithium-ion batteries (LIB) are the most used cell technology in electric vehicles (EVs) in recent years and today. Since 2008 the first series produced vehicles using LIBs have been on the road and the number of vehicles that complete their first phase of life increases. So does the number of traction batteries that can be further processed (Eberhard and Tarpenning, 2006; International Energy Agency, 2022; Tesla Motors, 2010). There a several reasons for a vehicle traction battery completing its first life - a frequently used but outdated criterion is the threshold of 20 % capacity loss of its original capacity introduced by the United States Advanced Battery Consortium in 1996 or a remaining State of Health (SOH_C) of 80 % (U. S. Department of Energy, 1996). Today most car makers set the limit to 70 % (Canals Casals et al., 2022). Since modern vehicles have batteries with significantly increased capacity, remarkable increases in range are possible compared to earlier vehicles. Thus, drivers can accept greater capacity losses without restricting the day-to-day usability of their vehicles. Consequently, batteries with different remaining capacities are offered on the market. In addition to the end of the first phase of life due to significant capacity losses, the overall condition of the vehicle must also be considered. For example, the battery of a vehicle that is no longer roadworthy must be removed from it, the same applies to vehicles that are considered total damage as a result of an accident (Montes et al., 2022).

Forecasts show an increasing availability of traction batteries, which could reach a global supply of 29 GWh/y by 2025 and exceed 200 GWh/y in 2030 (Tyler, 2016). This prediction makes it clear that the used batteries should not be disposed of as mere waste, but that the cells, which already have a carbon footprint, can be given a second life (SL) – studies show a positive benefit of this approach (Zhu et al., 2021). Thus, reducing the negative environmental impact of their manufacturing, which accounts for up to 60 % of total production emissions. For example, a study shows a 57 % reduction in global warming potential when using SL storage in combination with a rooftop PV array compared to using a new battery storage system with a potential of up to 70 % under optimal conditions (Bobba et al., 2018; Richa et al., 2017). In addition to the vehicles being taken back by the Original Equipment Manufacturers (OEM), the increasing number of registered EVs means that third parties, including municipal recycling facilities, can expect to see more of them.

With the removal of the traction battery from the vehicle, the question arises as to whether it can be used again (reuse) or recycled (Kotak et al., 2021)? From an ecological point of view, both variants are preferable to disposal - however, the final decision will be made from an economic point of view, where in an ideal circular economy the battery is recycled at the end of service life. Batteries, modules or cells which are capable to perform in SL applications embody the carbon while recycled raw materials show a four times lower carbon footprint than raw materials from primary sources (Linder et al., 2023). One of the biggest cost drivers in both approaches is currently the manual work and the duration of individual work steps. The decision described above should be easier for the OEM than, for example, municipal recycling facilities. The former knows about the properties of the built-in cells, they may even know the history of their use - for the latter, a traction battery is like a black box built into the chassis of a vehicle. Therefore, before the battery is screened, the disposal company knows little about the current condition of a traction battery. In addition to the economic risk of how the battery is priced when it is purchased, there is also the risk of further processing a cell with an unknown history and therefore an unknown SOH. Consequently, a cost-effective and therefore quick identification of the SOH is sought. The following sections provide an overview of the technical procedures and metrological approaches in the further analysis of traction batteries.

2. Technical Procedures

If a battery is to be classified for its suitability for a SL application, it typically goes through a multi-stage process. Since the classification of SL cells is still a relatively new field, there are few publicly available procedures on how to perform it. Today there is only the UL1974 which proposes safety operations and performance tests for retired batteries – without elaborating steps and further details (Underwriters Laboratories, 2018). To be clear this is not a problem with standardization, it is a real-world problem with different designs of batteries for real world applications having different form factors, terminal designs, chemistries and so on. This problem will get worse with a prediction of up to 250 new car models by 2025 and their battery systems specially designed for the vehicle (Engel et al., 2019). The technical procedures for evaluating the cells are rarely published in the literature. Except for Chung, Schneider, and Zhao (Chung, 2021; Schneider et al., 2014, 2009; Zhao, 2017). Overall, their technical procedures can be described as follows:

(i) Disassembly of gathered battery or module
(ii) Performance evaluation
(iii) Sorting and regrouping
(iv) Development of control strategies for SL applications

In some cases, the steps mentioned are carried out iteratively starting at the battery pack level down to the single cell level. Rejection of the battery pack, module or battery cell is possible at every stage of the steps (i) to (iii). Step (iii) and (iv) are not subject to this paper.

2.1 Visual inspection

Step (i) is required regardless if the complete battery, the modules or cells should be reused. This step should gather all accessible metadata like manufacturer, production date, batch, chemistry, configuration, information concerning the first life, reason for battery being taken out of service – the rationale behind this is documented in the UL1974. The idea is to get the best possible understanding of the design of the battery, the cells installed in it and other components such as the cooling or the battery management system

(BMS) for further analysis. The BMS in particular can be used for further analysis, provided that communication is possible. If historical measurement data is stored and accessible, they can provide additional insight. Typically, these systems are proprietary and communication with them is only possible for OEMs - so this option is not available for other remanufacturers (Lacap et al., 2021).

After the gathering of the available data a visual inspection of the vehicle follows. Visible damage to a vehicle or to the battery itself can serve as an initial basis for the decision whether to buy a vehicle or the battery and repurpose it, or to recycle it. The visual inspection at this level offers an uncomplicated rejection procedure, especially for municipal recycling facilities. Depending on how intensive the inspection of the vehicle is carried out, e.g. by removing the battery, the time required to carry out the work also increases. The general rule is: the more that is disassembled, the higher the time and associated costs. Rallo et. al report a total of 60 minutes spent for removing the traction battery of a Smart ForFour, 300 minutes for disassembling the battery into modules and additional 165 minutes for disassembling the modules to cell level. at each stage at least two workers were engaged in the dismantling (Rallo et al., 2020). The OEMs currently also have the advantage here, as they at least have the design data for the battery, often log the service of the vehicle and have the option of reading out diagnostic data. In the same way, it is easier for the OEMs to assess, in the case of an accident vehicle, which damage can be accepted or which directly leads to the rejection of the battery. Visible reasons for a rejection could be:

- bend or damaged casings and enclosure or support structures, loose connections
- damaged cells, electrolyte leakage, traces of burning
- damaged wiring, damaged insulation,
- leaking coolant, blocked fans

Even at this stage, attempts should be made to minimize the use of labor in order to keep the costs for using the battery in a SL application as low as possible. In addition to the economic reasons for not carrying out a visual inspection by workers, the associated inaccuracy of such an inspection and possible health hazards for workers due to damaged batteries can also be cited (Nedjalkov et al., 2016; Sobianowska-Turek et al., 2021). Consequently, non-contact examination methods, such as the digital image-based approaches or the X-ray-based techniques are preferable, but are practically never used at vehicle level. Systems such as those used for examining shipping containers or at airports may offer enough resolution to detect damage and leaks in built-in vehicle batteries (Kolkoori et al., 2015; Kwak et al., 2004). Villarraga-Gómez shows the application of non-destructive inspection over the complete chain of material research up to pack assembly of traction batteries (Villarraga-Gómez et al., 2022). Signs of aging in cells can already be detected on a laboratory scale, as shown by Bond and Hou (Bond et al., 2022; Hou and Li, 2018). Batteries that pass the mechanical evaluation are further inspected by direct measurements or broken down to modules or cells.

2.2 Disassembly

If the complete battery pack can be reused in a SL application step (ii) solely consists of removing the battery from the vehicle and removing connectors and cables, electronic components, and cooling components (Lander et al., 2023; Tan et al., 2021). But with the shown scarcity of data in mind, a more in-depth breakdown at module level is obligatory for third parties in order to be able to make reliable statements about a battery finally in step (iii). Additionally, a direct reuse of a battery pack is uncommon (Zhou et al., 2020). A reason for this is that the configuration of serial and parallel strands is often not suitable for the SL application, e.g. in terms of capacitance, voltage and current or solely form factor of the pack. However, there are applications that use used and previously rated battery packs as stationary storage - if necessary, however, individual packs can be excluded from use (Anderson, 2020; Kendall et al., 2022). Used battery packs are seldom stacked, because there is no need for a higher voltage, instead they are connected in parallel for increased capacity with the benefit, that a faulty pack can be disconnected without impairing the function of the entire system. Current flows between packs with different voltages are possible, to circumvent this these are often used in combination with converters and a BMS designed for the application, which increases the overall cost of the system (Montes et al., 2022), theoretically the old BMS of the

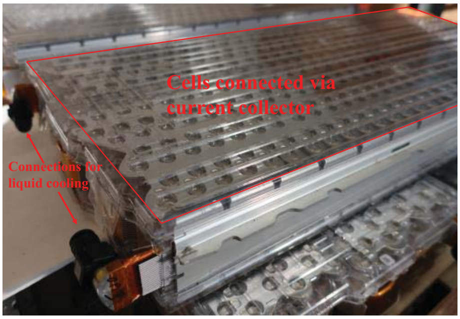

Fig. 1 Battery module of a Tesla Model S with spot welded current collector and connectors for liquid cooling.

vehicle could be used, however this is often waived for security reasons, since serious manipulations have to be carried out on the existing system (Rallo et al., 2020). In particular, the connection of other battery packs that have not been examined in detail is a great risk, because of a bad consistency among battery cells in the battery packs, which is related to the various and complex service life of a traction battery and so the diverse decay of these. The packs must therefore be evaluated for safe deployment, this corresponds to step (iii), which is further explained in the next section.

In the iterative process of dismantling the traction battery into smaller units it becomes evident, that traction batteries for use in EVs are designed with ruggedness in mind in terms of their mechanical construction, they are not designed with the approach of design for recycling. This can be seen in the construction of the outer shell and also in the construction of the current collectors inside. Figure 1 gives an idea of the effort required to extract a single cell from the spot-welded current collector and the surrounding cooling fin of a Tesla Model S module.

2.3 Performance Evaluation

Step (iii) shows that an assessment can be made in two dimensions, the first dimension is the remaining capacity of the battery, the second dimension is the performance of the battery - performance tests in particular offer the possibility of a quick evaluation of the battery, but at the same time there are dangers due to the high chemical energy content of the connected battery pack (X. Feng et al., 2018; Ismail et al., 2013; Wang et al., 2012); the particular difficulties here are suitable monitoring of the voltages of serial connected strands and the temperature distribution over the entire battery. If connected and available the serial strands are monitored by the original BMS – if removed from the vehicle these cables or connections of the serial strands can be monitored with data loggers, giving insight into the behavior of the modules, Figure 2 shows such a connector of a VW ID.4 module. However, it should be noted here that a weak module or cell affects the output power and thus compromises the overall output power of the battery. In such a setup, charging and discharging tests have to be carried out with low C rates while observing strict termination criteria in combination with strict monitoring of the relevant parameters, like voltages, current of the battery pack and distributed temperature measurements (if possible, in combination with internal sensors). The typical tests for capacity and internal resistance of a battery pack can last up to several days. During high-performance testing, another difficulty arises from the need to cool the battery, if necessary. Some of the older EVs that are now reaching their EOL do not have integrated cooling for the traction battery, an example would be the Nissan leaf (Lacap et al., 2021). Newer cars often use liquid cooling, which adds additional difficulties in the test setup, as shown in Table 1. Without appropriate cooling charge and discharge rates may have to be reduced - this is compounded by the fact that potential exposure limits are often confidential and only known by the OEM. Additionally, the Table shows the battery configuration of older and newer EV traction batteries. Not only do older Tesla models stand

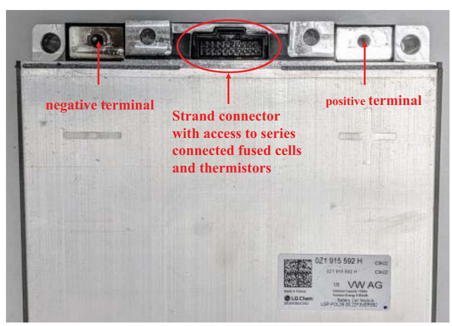

Fig. 2 Power terminals and 22 pin connector of a VW ID.4 module.

Table 1. Module configuration and cooling option of different EV generations.

Vehicle (Year)	Battery Config. **S**eries **P**arallel	Cooling
Telsa Model S 85 kWh (2016)	16 Modules á 6S74P[1]	Liquid[1]
Tesla Model 3 53 kWh (2020)	4 Modules; Total 96S31P[2]	Liquid[3]
Tesla Model Y 60 kWh (2022)	106S1P[2]	Liquid[4]
Nissan Leaf 24 kWh (2010)	48 Modules á 2S2P[2]	Passive Cooling[3]
Nissan Leaf 40 kWh (2022)	96S2P[2]	Passive cooling[3]
Lucid Air 118 kWh (2022)	220S30P[2]	Liquid[5]
Mercedes EQC 108 kWh (2022)	6 Modules Total: 96S4P[2]	Liquid[3]
VW ID.4 82 kWh (2023)	12 Modules á 12S2P[2]	Indirect[6] cooling

out with the particularly high number of cells connected in parallel; the newer Lucid Air with its 118 kWh 800 V battery pack has 6.600 connected cells in it. In particular, the decreasing number of parallel strands over the years within the battery or the modules could provide a simplified access to analysis and ease the removal of cells from a module.

With the special safety requirements regarding the electrical and chemical energy of a traction battery and the cooling that may be necessary, it becomes clear that performance tests at module level in particular are preferable. The next section gives insight into various testing methods and their execution time.

3 Testing methods

In principle, all methods from classic laboratory measurements can be used to measure aged traction batteries. However, since an unknown basic state of the traction battery can be assumed, the investigations should be carried out in a particularly protected, air-conditioned environment under initially reduced load scenarios. In accordance with the protection of man and machine, the test facility should have options for inerting, extinguishing devices and the removal of excess pressure.

In the best case, the sensors installed in the battery pack or module can be accessed during the measurement, otherwise, to prevent damage or destruction of the test object, the module or pack must be dismantled to the extent that the necessary sensors can be connected for monitoring. In both cases extensive knowledge of the structure of the battery is required. The lack of access to sensors and the difficult access to measuring points, for example due to glued or welded housings, represent a major safety risk for the measurement.

Before performing the characterization, the battery must first be brought to a known state. To do this, the battery is charged at a defined charging rate, typically C/3 across different standards (ISO 12405-4, 2018; SAE International, 2020). To reduce possible cell drift, the battery is then completely discharged and charged once with C/3. As a preconditioning the so-called standard cycle (SC) is usually repeated at pack and module level before each characteristic measurement.

The measurement of the key electrical parameters capacity and internal resistance of the batteries is discussed below.

3.1 Capacity Measurement

The capacity determination, typically based on a discharge, enables the remaining capacity and thus the SOH_C of the battery to be determined. To be able to compare different batteries with each other, a constant discharge rate of C/3 is typically used initially. When determining capacitance with constant current, typically only a constant current phase is run through, which results in the discharge voltage being reached earlier due to internal overvoltages at the internal resistance. The determination of the static capacitance enables a fast determination of the capacitance. The test is normally performed at room temperature (25 °C). For further investigations,

[1] (Sharma et al., 2019)
[2] https://ev-database.org
[3] (Roe et al., 2022)
[4] (Tesla Motors, 2022)
[5] (Rawlinson, 2021)
[6] (Volkswagen, 2020)

the current intensity and the ambient temperature can be varied in the following. This enables a far-reaching determination of where and in which application the battery could be further used. The duration of a capacity test is dependent on the remaining capacity and the used charge and discharge current. Rallo reports a duration of 440 minutes for the assessment of a 52 Ah battery (Rallo et al., 2020).

3.2 Internal resistance measurements

The internal resistance of a battery is a key indicator for its performance, as it defines the electrical losses occurring during usage of the battery. The internal resistance can be measured using AC and DC measurement methods, but it must be noted that the results performed with DC and AC approaches are not directly comparable.

3.2.1 AC resistance

The galvanostatic AC Resistance Measurement is a method where a constant current and frequency are applied to the battery to determine the AC resistance. The small-signal measurement is usually performed prior to the EIS. With a constant frequency of 1 kHz and a current between 1 mA to 10 mA, the procedure requires high precision measurement equipment to properly measure the internal resistance that is usually within the milliohm spectrum. (J. Feng et al., 2018; Schweiger et al., 2010).

3.2.2 Electrochemical impedance spectroscopy

The EIS is an AC small-signal measurement method which is widely used method. (Kehl et al., 2021; Middlemiss et al., 2020) By applying a small sinus shaped input signal and vary the frequency the complex and frequency dependent impedance of the battery can be identified. Enabling the differentiation between ohmic, capacitive and inductive system behavior (Orazem and Tribollet, 2017). Muhammad et al. report a duration of 15 minutes for an impedance spectroscopy of a single cell, such a duration could be acceptable even with high number of packs, modules or cells to be evaluated (Muhammad et al., 2019). Due to the many internal resistances, the impedance spectroscopy is only conditionally suitable for packs. It is used at module or cell level, where the duration is highly dependable on the used frequency and number of sweeps.

3.2.3 Pulse measurement methods

There are many different approaches which are commonly used to determine the internal DC-resistance using pulse- or so-called relaxation measurements (Brühl 2017; Li et al. 2016). The general procedure is based on a stepwise charging and/or discharging of a battery to determine the DC resistance based on the voltage response and given applied current. Whereby the exact time and the applied current pulse to determine the resistance may vary. (Kremzow-Tennie et al., 2022; Scholz et al., 2018; Schweiger et al., 2010). Muhammad et al. report a hybrid pulse power characterization (HPPC) which is capable of discriminating strong and weak cells within a duration of 2 minutes (Muhammad et al., 2019). HPPC tests offer a promising chance for a quick and reliable assessment of retired LIBs, even at scale.

3.2.5 Constant current resistance measurement

Continuous determination of internal resistance typically relies on a constant current measurement, in which the battery is continuously discharged or charged at a constant DC current. By comparing the recorded voltage curve with the open-circuit voltage, the resistance can be determined with the aid of the known amperage and ohms law (Chen et al., 2017).

3.2.5 Incremental capacity analysis

The incremental capacity analysis (ICA) is a further method to estimate the state of health (SOH) of Li-ion batteries. The incremental capacity (IC) is the derivative of capacity against the voltage (dQ/dV). Krupp et al. use the ICA for the SOH estimation of battery modules with series-connected prismatic cells of the type $LiFePO_4$ with a capacity of 40 Ah (Krupp et al., 2020). In his publication He identifies the peaks of the IC curve. Based on the identified peaks, the authors are able to use the information for the analysis of battery aging and SOH estimation, respectively (He et al., 2020). The results of both publications underline, that the ICA is a promising method to identify the SOH of battery module

4. Conclusion

This paper shows possible approaches to evaluating batteries at the end of their first life. Difficulties in the investigation at pack level or module level are shown through the construction of these as well as possible approaches for the assessment with testing equipment are explained. The challenges for third parties when evaluating aged batteries were also shown. Finally, different measuring methods for determining the SOH_C were presented and their suitability for fast analytical methods was considered. For municipal recycling facilities, in contrast to OEMs, there are currently still considerable hurdles in the health assessment of LIBs - with the increasing availability of traction batteries, there is a sufficient need for solutions for the fast evaluation of these, both for safety reasons and from an economic point of view.

Acknowledgement

The authors would like to thank the German Federal Ministry of Education and Research for funding this work. (Projet: UniZuB 03XP0500A)

Also, we would like to thank the Reviewers for spending their time and effort reviewing the manuscript. We sincerely appreciate all valuable comments and suggestions, which help to improve the quality of the paper.

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