D3.4

# Labelling and certification protocols for second life batteries

Grant Agreement n°776680

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# 1. SUMMARY

This report discusses various aspects of the repurposing of (industrial) lithium batteries. Reuse is first placed in the broader context of the circular economy. Europe places a strong emphasis on developing its own processing industry to reduce its dependence on imported raw materials necessary for the production of lithium batteries. It is of course best to avoid the waste status by repurposing batteries in new applications when they no longer comply with their original application. Then, the UL1974 standard, which is the only immediately applicable one for second-life use of batteries, is analysed and reviewed.

The possible technical parameters that can be used in the evaluation of battery packs and cells are then discussed, including selection criteria such as internal resistance, capacity, impedance and self-discharge. The discussion on practical aspects of repurposing differentiates direct repurposing, without dismantling, and repurposing after dismantling. In the second case, it is useful to know the different cell packaging and joining techniques, the types of cells and thermal management. These analyses then lead to the proposal of a test procedure in order to select the batteries and modules efficiently and cost-effectively. A key element in the selection procedure is to have foreseen dissimilar second life applications, so that incoming batteries can be sorted according to their quality towards different usages.

The regulatory aspects are dealt with, starting with an evaluation of the 2006 Batteries Directive, based on a thorough analysis published in 2019. It described the results achieved but also several shortcomings. This resulted in a new, broader proposal for regulations at the end of 2020 and adopted by the European Parliament beginning 2022. Collection and recycling targets are tightened up and reuse is explicitly included in the new proposed regulation. Performance and durability requirements for batteries are added, similar to those imposed on e.g. household appliances. This should reduce the amount of battery waste and extend its life. Further efforts are made to ensure the availability of information on each battery, through the use of harmonized labels including manufacturer, date of manufacture, battery type and chemistry, hazardous materials and critical raw materials. This could evolve into a more extensive “battery passport” in which the history (repair, repurposing) is also kept and can be consulted online.

In addition, standardization processes have started on the international level, with the development of IEC 63330 and IEC 63338, which will deal with repurposing in their own way. Interesting aspects are the focus on the original safety area and considering several applications to repurpose batteries. These aspects have been dealt with in the proposed selection procedure.

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## 2. INTRODUCTION

The aspect of “re-use” and “repurposing” is becoming an important theme. This is partly reinforced by the EU's commitment to the circular economy, by stressing the life span and the useful application of batteries. The reuse of industrial and EV batteries is explicitly included as a “waste treatment method”.

Within the CIRCUSOL European project[1], WP3 deals with the development of a circular supply chain, and the objective of Task 3.4 is to provide protocols for labelling and certification of batteries for second-life. Like in the other battery-related tasks of the project, it was decided to focus on lithium-ion batteries from EV and their reuse in stationary applications. This technology represents by far the largest share of EV batteries today.

The report examines existing standards dedicated to second-life batteries. , Then, the ongoing standardization work is discussed and analysed both at European and International level. After these reviews, this report proposes a flowchart for batteries assessment and details the main test procedures. The approach of repurposing the batteries can be divided into two parts: a preliminary stage in which quantitative selection criteria are drawn up and where it is checked whether cooperation from the original battery manufacturer is possible.

The preliminary phase can consider both the direct repurposing of the entire pack or its dismantling before repurposing. This preliminary stage provides the basis for making the necessary choices in the actual repurposing process.

Then, a test and selection procedure is proposed optimising the labour and time requirements while obtaining the maximum useful information. By first performing tests that are not very time intensive and the possibility to skip testing of modules if the reworked battery pack is tested or validated in its entirety, the turnaround time can be shortened.

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[1] https://www.circusol.eu/en

# 3. CIRCULARITY ASPECTS OF LI-ION BATTERIES

## 3.1 THE CIRCULAR ECONOMY APPROACH

This study into repurposing of batteries is based more fundamentally on the principle of the circular economy. This paradigm gives a different view on products and their life cycle. Waste can become a raw material and products can be replaced by services. The "big picture" is a famous representation depicted in **Figure 1** This approach is used by the European Investment Bank (EIB) and described in their report “The EIB Circular Economy Guide – Supporting the circular transition”, 2018[2] . In this figure, reuse in another application or repurpose is not explicitly mentioned. Reuse, on the other hand, is part of a slightly different view described in the mentioned EIB guide: the 9R strategies. Some add another 10th R, which is also given below and also appears in **Figure 1**.

| | |
|---|---|
| R1 Refuse | Make the product obsolete by giving up its function or by offering the same function via a radically different (e.g. digital) product or service. This may relate to a wind-up flashlight that makes (a large) battery unnecessary. |
| R2 Rethink | Intensify product use (e.g. through a product-as-a-service approach, through models based on reuse and sharing, or by marketing multifunctional products). This is the current trend for portable (garden) tools, namely that one battery can be used for many devices and can also be exchanged between different brands.[3] [4] |
| R3 Reduce | Increase efficiency in the manufacture or use of products by consuming fewer natural resources and materials. This is possible with batteries that last longer. Battery standards include endurance tests to make this visible. |
| R4 Re-use | Reuse of a product that is still in good condition and fulfils its original function (and is not waste) for the same purpose for which it was designed. This involves inserting an EV battery into another electric vehicle. |
| R5 Repair | Repair and maintain a defective product so that it can be used in its original function. It speaks for itself. With bicycle batteries, this is done at the cellular level. With EV batteries, a module is replaced. Replacing cells is here virtually impossible (see the section on production methods later). |
| R6 Refurbish | Restore an old product and bring it up to date (to a specified quality level). Unfortunately, the battery cells in a battery cannot be rejuvenated through a special action (which is nevertheless regularly promised by scammers). What can happen is that the modules in a battery pack are replaced by modules with a larger capacity. Nissan does this with used modules that are newer than the modules to be replaced[5]. This makes it very similar to the following strategy, except that it must become a new product. The battery management system can sometimes be adapted to allow a wider use, for example a deeper discharge. The battery cooling may be adapted to allow for more cooling or better heating in winter. |

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[2] https://www.eib.org/attachments/thematic/circular_economy_guide_en.pdf

[3] https://www.cordless-alliance-system.com/

[4] https://www.powerforall-alliance.com/

[5] https://insideevs.com/news/337360/nissan-introduces-2850-refabricated-batteries-for-older-leaf/

| | |
|---|---|
| R7 Remanufacture | Use parts from a discarded product in a new product with the same function (and in new condition). This can be done with the components in a battery pack (modules, BMS, cooling, safety device, wire harnesses) that are included in a new pack[6]. A very similar example is in the footnote about Nissan in the previous strategy. |
| R8 Repurpose | Use a surplus product or parts thereof in a new product with a different function. This can be done by giving the battery packs a second life in another application. This is discussed in detail in this report. |
| R9 Recycle | Recover materials from waste to be reprocessed into new products, materials or raw materials, either for the original or for other purposes. It includes reprocessing of organic matter, but does not include energy recovery and reprocessing into materials that will be used as fuel or fillers. This is of course also possible with batteries. Ideally, the materials are reprocessed in such a way that they regain the quality of battery raw material. Battery recycling is organised by the collection of batteries. The organisation of this is obligatory in each European country as laid down in the Battery Directive. |
| R10 Recover | Recover energy from waste incineration. This is not the intention with batteries because they have to be collected separately, so not ending up in the regular waste stream. |

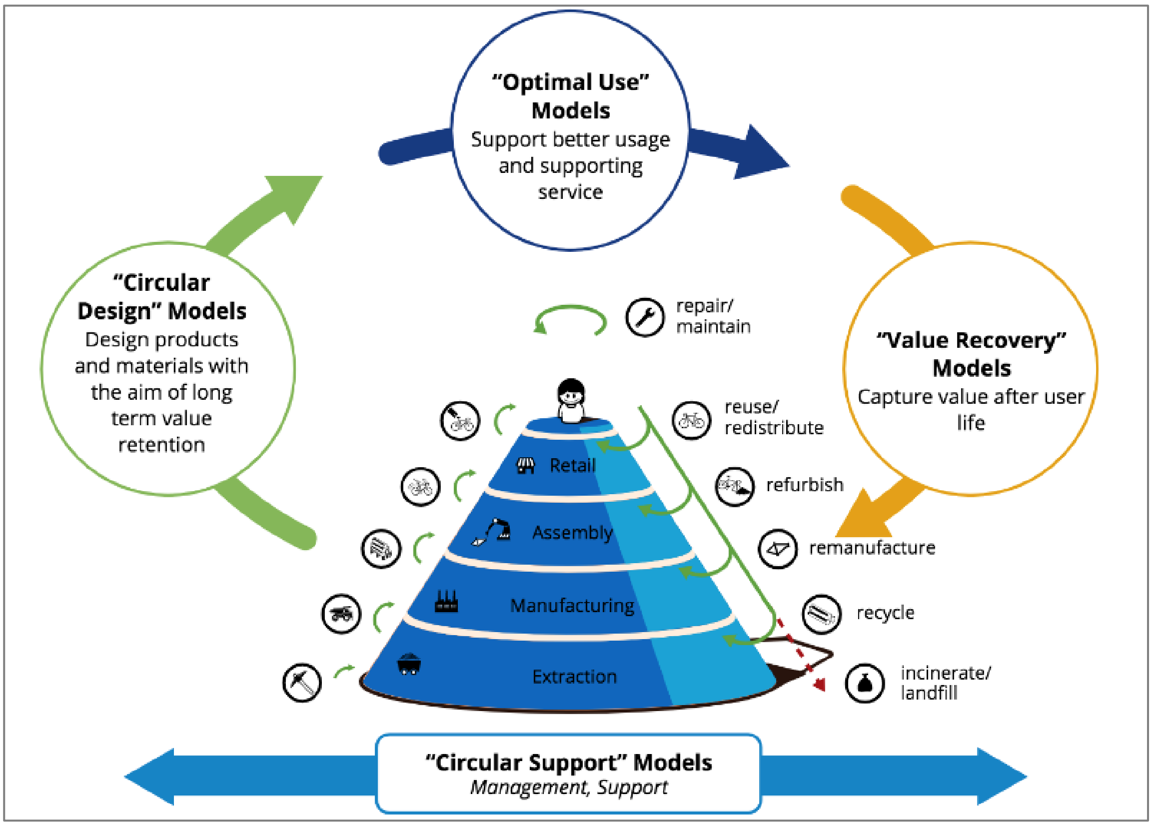

Figure 1: The approach to a circular economy[7]

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[6] A catalog of components to be purchased can be consulted, for example, at: https://www.secondlife-evbatteries.com/collections

[7] Achterberg, E., Hinfelaar, J., Bocken, N. (2018). The value hill business model tool: identifying gaps and opportunities in a circular network; https://docplayer.net/86718304-The-value-hill-business-model-tool-identifying-gaps-and-opportunities-in-a-circular-network.html

## 3.2 APPLICATION TO BATTERIES

The market for electric vehicles has increased very significantly in recent years, and most of them use Li-ion batteries. **Figure 2** shows the global demand for Li-ion batteries and the breakdown across sectors, with a projection to 2030. Since EV batteries lifetime is about 8-10 years, this leads to an estimation of one million batteries retired from EV application in 2030 (in the European Union). The end-of-life management of EV batteries is currently regulated by the EU Battery Directive (2006/66/EC), and decommissioned EV batteries are 100% collected. Recycling processes have been developed, but they are not easy to implement due to the wide variety of Li-ion chemistries. A main recycling goal today is to recover cobalt, which is a high-value metal and is on the critical raw material list for EU. Although the recovery rate of other less valuable metals such as lithium and copper is low today. Nickel is recovered but not in the most suitable form currently for the battery industry, Technical processes are becoming available and their recovery may become viable in the future[8]. On the other hand, some battery types, such as LFP batteries, contain almost no valuable metals, which makes recycling economically difficult. Most studies (mainly LCA) do converge towards a positive environmental impact of re-using batteries and delaying recycling[9], especially concerning $CO_2$ emissions, water consumption, energy demand, and use of fossil resources.

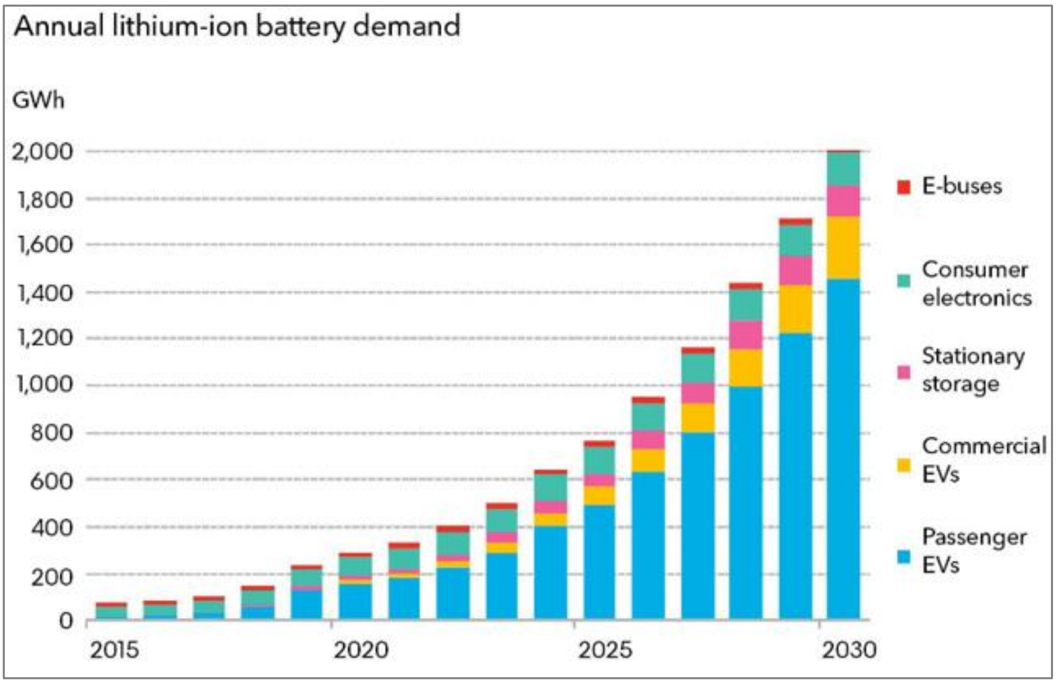

Figure 2: Global demand for lithium batteries[10]

The 9R strategy detailed above is of course important for batteries. The Batteries European Partnership[11] , set up by the European Commission and led by sector organisations, has made circular design a key action point. This aims to evaluate the design and materials of batteries from the point of view of reuse, recycling and

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[8] EU JRC science for policy report, “Lithium ion battery value chain and related opportunities for Europe” (2016)

[9] “Développement d’une filière intégrée de recyclage des batteries lithium”, French National Industrial Council, 02/2020

[10] https://about.bnef.com/blog/will-the-real-lithium-demand-please-stand-up-challenging-the-1mt-by-2025-orthodoxy/

[11] https://ec.europa.eu/info/files/european-partnership-industrial-battery-value-chain_en

repairability. It conducts analyses of battery and battery system design and defines common principles, tools and methodologies for the evaluation of circular design.

When batteries reach the end of their EV life, they often still have 70-80% of capacity. Several industrial actors are investing to develop a "second life" for these batteries, which means exploiting this remaining capacity for stationary storage applications such as grid stabilization, industrial, commercial and residential consumption. This approach uses either R4 re-use or R8 repurpose, as graphically shown in the diagram of **Figure 3**.

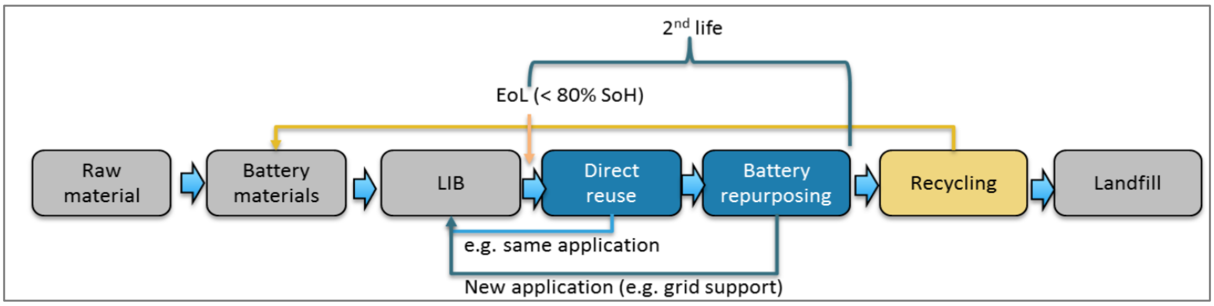

Figure 3: the life stages of a battery (source: Ecodesign batteries study[12])

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[12] Tim Hettesheimer, Antoine Durand, Ecodesign batteries – 2ndstakeholder meeting presentation of task 6 (without LCA part), May 2nd, 2019 https://ecodesignbatteries.eu/sites/ecodesignbatteries.eu /files/attachments/ED_Batteries_SM2_Task%206.pdf

## 4. REVIEW OF EXISTING STANDARDS

The first step in the context of CIRCUSOL was to perform an inventory of the current regulation and the standardization regarding batteries, starting from the database of batteries standards (see 'batterystandards.vito.be') established during the European project STALLION (09/2012 – 12/2015). It appears that in their wide majority, these standards do not make any distinction between a new and a second-life battery. Whether it concerns performance or safety, the batteries have to satisfy the same constraints to be suitable for the application considered.

### 4.1 ANSI/CAN/UL 1974 EVALUATION FOR REPURPOSING BATTERIES

The only dedicated standard appears to be the ANSI/CAN/UL 1974 "Standard for evaluation for repurposing batteries" published 10/2018, a few months after the beginning of the CIRCUSOL project. UL1974 was set up in order to satisfy an identified request from industry, and covers the sorting and grading process of battery packs, modules and cells that were originally configured and used for other purposes, such as electric vehicle propulsion, and that are intended for a repurposed use application, such as for use in stationary energy storage and other applications. It applies to all battery chemistries (Li-ion and others) and also to electrochemical capacitors.

UL1974 proposes a list of essential guidelines and requirements to be followed by an eventual manufacturer, starting from the collection of batteries that were originally used for other purposes, up to the repurposed product to be used in other application.

The main body of the document is split in four main sections:

- Construction
- Quality control and safety of facilities for repurposing
- Examination of incoming samples
- Performance

The requirements for packing and shipment, quality control and safety of facilities are similar to battery standards requirements for first use batteries. Concerning marking, the nameplate shall contain the date of repurposing manufacture, which may be in the form of a code, and the repurposed parts shall also be marked ”Repurposed” and ”UL 1974”.

In the “construction” section of the document, the design criteria of the repurposed battery (material, wiring, insulation levels, controls...) mainly refer to the application-specific battery standards.

#### 4.1.1 GENERAL APPROACH (§ 7)

Section 7 of the standard defines some clear rules for batteries second-life use:

> A fundamental requirement is that the cells, modules and their peripherals (such as wiring, connections, contactors…) must comply with the relevant standards applicable to the new application. The repurposed battery as a whole must therefore be regarded as a new product and conform to the relevant standards and norms for that application. Take here into account the mechanical aspects of the housing, electrical and thermal insulation, flammability, etc.

The battery must not be used past its expiry date ('calendar expiry date'). This date must be specified by the manufacturer. Today, however, this is rarely the case and if available, this date does not necessarily reflect a bad SOH.

If the BMS or other protection functions also remain integrated in the recycled battery, its proper functioning should be evaluated, again in light of the subsequent application. In practice, this may mean that documentation, adapters or diagnostic software must be made available by the original manufacturer.

The history of the battery should be read and followed, especially for detecting previous battery 'misuse'. Information about the SOH must be read from the BMS. Again, this actually requires the cooperation of the original producer.

The battery should not show any external visual damage, nor should this be found during disassembly, unless it is minimal. What is minimal must be laid down in a separate regulation.

The standard prescribes a routine test.

### 4.1.2 INSPECTION PROCEDURE (§ 18)

In the "Examination of incoming samples" part, advised diagnostic and inspection steps are detailed at different battery architecture levels: battery pack, battery module, battery cells and BMS and auxiliary systems. The definition of the performance assessment steps is split between the same architecture levels.

The first step is an analysis of the battery history and available information. This includes especially previous misuse situations and information from the BMS on the battery's state of health. The list of information to be gathered is exhaustive, and all the information of the list might be hard to collect in a real life situation, what is admitted by the repeated remark 'if available'. It is about statistical data of average, maximum and minimum values acquired by the BMS. This step also includes visual inspection of the battery pack/system and its components and parts to determine that there is no visible evidence of damage.

The detailed procedure for the incoming used batteries is described in section 18 of the standard, and contains the following steps:

Initial and rejection procedures (§ 18.3)

The manufacturer of the used battery (the repurposing manufacturer) must review the available information about the incoming used batteries and thus carry out an initial rejection process. Parts that have been exposed to certain conditions that could have an impact on safety will no longer be retained for further processing. These circumstances are not limited to severe ones (immersion, fire, crash…) but also for performance issues, physical, and other signs of damage. All non-rejected parts are provided with a serial number.

Visual inspection (§ 18.4)

Prior to disassembly, all battery components should be visually inspected for visible damage: cracks, swelling, gas leakage, discoloration or traces of fire. All damage must be assessed according to the procedures of the repurposing manufacturer before further processing the battery

Collection and analysis of BMS data (§ 18.5)

An important source of information about the battery's SOH may be the BMS. Access to this data can therefore contribute a lot to the selection process. The standard specifies that at least the following information must be extracted from the BMS, if available:

Average, maximum and minimum values of voltage, current, temperature,

Total exposure time to extremes of the stated values,

Total incoming and outgoing charge,

Saved error messages,

Number of contactor operations. Contactors, especially those for high voltage and DC interrupting, are typically specified for a very limited number of interrupts at their rated current. Indeed, the arc that occurs momentarily when opening will affect the internal contacts. In the worst case, this can lead to fused contacts and thus an uninterruptible connection.

### Disassembly and examination (§ 18.6)

Visual inspection of the battery pack and components:

- damage, deformed housings, loose connectors,
- swelling, leakages, burns
- frayed wires or insulation, discoloration
- damage to thermal management, such as coolant leaks, blocked fans

If damage is found, rejection is necessary, excepted for minor damage. Then it must be estimated whether the nature and impact on safety is small enough to further disassemble the battery and use it for reuse, by testing the battery.

It is absolutely necessary to discharge the pack before proceeding with the disassembly. The pack can then be disassembled to its smallest possible parts that are suitable for reuse, for example into modules or individual cells.

A log of the process is kept and each part is numbered.

### Storage condition tracking (§ 18.7)

Batteries that are suitable for repurposing are stored and monitored:

Ambient temperature and humidity, with minimum daily recording.

Open-circuit voltage at the start and end of the storage procedure. The self-discharge that can be derived from this must be compared with the acceptable limits set by the repurposing manufacturer

Measurement data of charge and discharge sequences that are part of the storage time are tracked

### Grading of batteries for repurposing (§ 18.8)

This subsection mainly indicates that the manufacturer must have a system to evaluate and sort cells or modules so that newly assembled packs are built from matched modules or cells. This is to avoid potential performance or security issues later on. The value of a remanufactured pack is derived from its homogeneity in aging. The testing itself is described in section 19.

### 4.1.3 TEST PROCEDURE (§ 19)

The standard then describes a sequence of routine tests, to be conducted by the repurposing manufacturer as part of the analysis of the incoming battery assembly, prior to any disassembly procedures. The level of information gathered during the first phase will directly affect the procedure to be defined for that. These tests will enable the definition of the "smallest intended disassembled unit for repurposing". These tests include:

Open circuit voltage of the incoming packs, modules or cells

The measured values must then be referenced with each other and any deviation is recorded. Cells or modules with a voltage lower than the minimum allowed value will be rejected, others will be subject to further tests.

High voltage insulation test

The insulation resistance of the parts of the battery that can become live to the chassis and 'dead' parts must be measured. To do this, 500VDC must be applied for at least 60s. The measured resistance must be greater than 100 Ohm/V, similar to what is described in other DC bus isolation standards. Batteries, modules or components with an insulation resistance lower than this value must be rejected.

Capacity test

A capacity test of the battery (cells, modules or the complete pack) must be performed, based on a standard capacity test of the repurposing manufacturer. The battery is charged at room temperature, followed by a rest period of 1 to 4 hours. This is followed by a constant current (CC) or constant power (CP) discharge, again at a rate determined by the repurposing manufacturer. Measured values are logged and cells or modules with deviating capacity values are rejected. The others can be sorted and classified as described in §18.8.

Internal resistance test

If the package as a whole is to be reused, additional resistance tests should be performed on those modules (or cells) where the thermal stress is highest. To determine the resistance, the battery is brought within 80-90% SOC, after which a discharge pulse is applied. Then follows a further discharge to 20%, a rest period, after which a new measurement is performed. The voltage drop divided by the pulse current gives the DC resistance. If the values are considered by the repurposing manufacturer to be unsuitable for the intended application, the modules or cells will be rejected.

BMS functionality test

If the BMS and any other safety functions are reused, a check must be carried out on the correct functioning of those functions.

Charge & discharge cycles

At least one full discharge-charge cycle is performed at room temperature, monitoring temperature, current and voltage. If the repurposed battery will be used below 0°C, a cycle should also be performed around that temperature.

Self-discharge test

In parallel with the internal resistance test, self-discharge should be checked at the module or cell level, or of the parts of the pack where the thermal stress is highest. To this end, the battery is fully charged and the OCV is logged 5min, 1h and 24h after charging. The values are finally compared with the allowable lower limit as set by the repurposing manufacturer.

Cell performance and safety characterisation

This falls outside the scope of testing directly on the battery, as the repurposing manufacturer has to set up a measurement campaign to collect data on the aging of cells representative of the repurposed battery packs. If the cells cannot be separated out of the modules, testing can be done at the module level. This data can then be used to gain a further understanding of the safety of used cells and modules, that repurposing manufacturers can use to improve their repurposing processes. Indeed, second-life ageing of batteries remains difficult to predict, as illustrated by the figure below, and it appears in particular that the first life history of the battery has a strong impact.

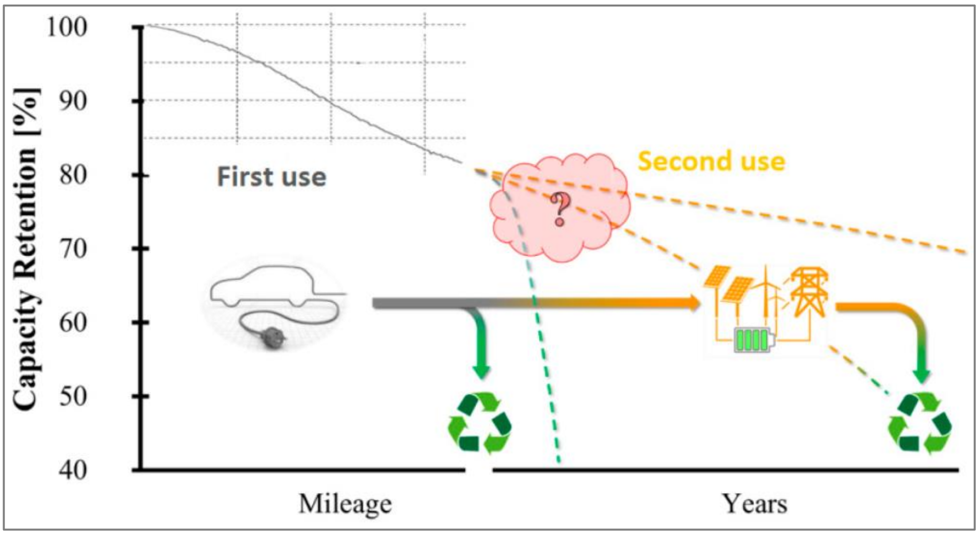

Figure 4: A measurement plan is needed to analyse performance and safety in a second life[13]

### 4.1.4 TESTING OF ASSEMBLED REPURPOSED BATTERIES (§ 20)

After the cells or modules have been tested and sorted, they are paired and assembled in such a way that no performance or safety problems can arise (e.g. due to excessive imbalance). The assembled repurposed batteries should also be tested. For this phase, the requirements to follow are those of the applicable standards related to batteries without distinction between first use or second life use: application-specific standards as well as transportation regulations. If samples are used to perform these tests, they must represent the "worst-case" scenarios in terms of SOH.

### 4.1.5 DISCUSSION

The approach of UL 1974 has the drawback of being highly labour-intensive. This is at on side hardly evitable: the dismantling and the testing are not very easily automated due to the variations in form, chemistry, architecture etc.,but the standard prescribes a lot of subsequent testing with long duration. In addition, important weight is laid on the battery "calendar expiration date", that is normally not available and that does not make real sense since the battery ageing does not (and by far) depend on time only, but also on its use and ambient conditions.

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[13] A.Podias e.a. (2018): Sustainability Assessment of Second Use Applications of Automotive Batteries. Ageing of Li-Ion Battery Cells in Automotive and Grid-Scale Applications. In: WEVJ 9 (2), S. 24. DOI: 10.3390/wevj9020024; https://www.mdpi.com/2032-6653/9/2/24

On the other hand, this standard provides clear procedures, which makes the second-life business possible, even if so much BMS data is required that an agreement with the original battery manufacturer will be needed in practise. The criteria and thresholds are to be defined by the repurposer, who knows best the intended application of the battery.

## 4.2 OTHER APPLICABLE STANDARDS

The remanufactured battery must meet the performance and safety standards applicable to its new application. Below is a list of the main standards that could be relevant depending on the selected application:

Standards related to performance and design

**IEC 62620**: 2014: "Secondary lithium cells and batteries for use in industrial applications"

**IEC 61427-2**: 2015: "Secondary cells and batteries for renewable energy storage Part 2: On-grid applications"

**UL 1973**: "Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications"

Standards related to safety

**IEC 62619**: 2017: "Safety requirements for secondary lithium cells and batteries, for use in industrial applications"

**IEC 62485-2**: "Safety requirements for secondary batteries and battery installations - Part 2: Stationary batteries"

**IEC 62485-5** "Safety requirements for secondary batteries and battery installations - Part 5: Safe operation of stationary lithium ion batteries"

More structured information and an overview of battery-related standards can be found on the BatteryStandards.info[14] website, which was developed across several European projects.

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[14] www.batterystandards.info

# 5. EUROPEAN REGULATION PROGRESS AND STANDARDS DEVELOPMENT

## 5.1 EUROPEAN BATTERY DIRECTIVE

At European level, the “Battery directive” is under revision. The new version will include important aspects to enable second-life use of batteries. This includes in particular making the battery’s historical data available, which is crucial especially for the safety assessment of the battery to be reused. In this section, the current version is presented, followed by a discussion of the updated version which is currently in discussion.

### 5.1.1 CURRENT BATTERY DIRECTIVE

The Batteries Directive came into force in 2006 and replaced the previous Directive 91/157/EEC. It is actually the only legislative text of the EU devoted entirely to batteries. The text covers the entire life cycle: from design and market access of the new batteries to end-of-life, collection and recycling of the used batteries. Batteries are divided into 3 categories: portable, vehicle and industrial. The latter includes all batteries designed exclusively for professional and industrial applications, or for electric vehicles (EVs). The vehicle battery category instead refers to the starter battery in the cars. The main aim of the directive is to reduce the negative impact of (waste) batteries on the environment. To this end, it outlines a number of objectives, with measures and principles to achieve them:

If used batteries are landfilled, incinerated or left behind, there is a substantial risk that a number of hazardous substances will be released via leaks or gas formation and cause damage to the environment or health. The directive addresses this by, among other things, a complete ban on the use of mercury and partially on cadmium. The directive does not address other external negative effects that affect the environment, such as the large-scale extraction of raw materials, or the use of energy and water-intensive recycling processes.

The Directive requires Member States to set up collection programs for used portable batteries, along with targets (45% in 2016). Member States must monitor and report on collection rates and recycling efficiency to the European Commission.

The Directive also requires Member States to set up collection programmes for used vehicle batteries (typically 12V lead-acid batteries), and to ensure that manufacturers of industrial batteries are not allowed to refuse to take back end-of-life batteries from their customers. Manufacturers of batteries and devices with built-in batteries are responsible for the (battery) waste that arises from their products.

All collected used batteries must be processed and recycled. To this end, the directive provides for minimum recycling percentages and the obligation to recycle lead and cadmium as much as possible. Naturally, these recycling processes must comply with all relevant European legislation.

#### EVALUATION OF THE DIRECTIVE

In April 2019, the European Commission published a report on the implementation, the impact on the environment and the internal market functioning resulting from the Batteries Directive.[15] In this section the main remarks are covered.

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[15] https://ec.europa.eu/info/sites/info/files/swd-report-batteries-accumulators-april2019_en.pdf

The general aim of the Batteries Directive to achieve a high degree of material recovery was not achieved. The recycling obligation was only defined for two metals, namely lead and cadmium. Targets for other valuable materials, such as cobalt and lithium, were not included. The way in which recycling is reported also falls short, as some Member States count the slags of the recycling process in the recycled volumes, while others do not. This is allowed if the furnace slag can be exploited usefully. Some Member States appear to be more lenient in this than others.

The target for the recycling efficiency of 'Other batteries' was set at 50% mass in the Directive. This does not appear to be sufficient to stimulate the recovery of lithium and (critical) materials such as cobalt from used batteries. Note that Li-ion batteries fall under the class of other batteries, whereas lead batteries and nickel cadmium batteries form the other two classes.

The possibility of giving the Li-ion type of battery a second life is seen as promising. Life cycle analyses do indicate that repurposing batteries for stationary energy storage results in more efficient use and a longer depreciation of the used raw materials[16]. A second life for batteries was not included in the Directive, because it was an unexpected development. Obstacles for new legislation include who is responsible for the repurposed batteries and how to report them. The unclear status thus prevents an ecologically and economically desirable situation in which batteries are used in applications other than those for which they were marketed (for example, as energy storage in homes). However, manufacturers argue that the lack of clarity regarding the extension of their responsibility (the so-called Extended Producer Responsibility, EPR) must first be resolved. That should clear up strange situations where the 'first-life' manufacturer would remain responsible for the battery during the second life, until it is finally recycled.

Further alignment of the Batteries Directive with Directive 2000/53/EC "End-of-life vehicles", and 2008/98/EC "Waste Framework Directive" is also considered desirable.

### 5.1.2 PROPOSED BATTERY REGULATION

After an evaluation of the Batteries Directive in 2019, as part of the Circular Economy Action Plan, the EC has finally worked out a new proposal for more extensive regulation. After several consultations in 2019 and 2020, it was published in December 2020 as "Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/ 1020." Li-ion battery production and development, meanwhile, is regarded by Europe as a strategically important element in the clean energy transition. A properly functioning recycling market and reuse can reduce the dependence on critical raw materials. The proposal is also harmonized with existing EU environmental and waste regulations. Originally, separate ecodesign regulations were also presented for batteries[17], in the same way as they exist for refrigerators and building lifts, for example. It has now been proposed to bring this under the regulation as a single entity for batteries. Product safety has also been added.

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[16] Bobba, S. et al. (2018) Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. Journal of Energy Storage. 19 pp. 213–225. https://doi.org/10.1016/j.est.2018.07.008

[17] Ecodesign preparatory study batteries, TASK 7 Report Policy Scenario Analysis, VITO, Fraunhofer, Viegand Maagøe, August 2019; https://ecodesignbatteries.eu/sites/ecodesignbatteries.eu/files/attachments/ ED_Battery_Task%207_V45_final_corrected.pdf

The proposal is therefore much broader than the 2006 directive, and consists of 13 measures that are translated into 79 articles and 14 annexes.

### Article 1 and 2

1. The regulations apply to all batteries, whereby a distinction is made between four battery types: portable batteries, vehicle batteries (only for starting, lighting and ignition), industrial and EV batteries (only for traction). Thus, EV batteries are now considered separately from industrial batteries. All batteries that do not clearly fall into the mentioned categories such as batteries for light transport vehicles and batteries for homes are classified as industrial batteries. The category of portable batteries applies up to 5 kg, above that they are considered industrial. Only batteries for military use and space travel are not covered by the regulations.

### Article 59.

2. The reuse of industrial (and EV) batteries is explicitly included as a “waste treatment method”. The choice was made for 'end-of-waste' criteria that batteries must at least meet in order to be suitable for reuse (a state-of-health (SOH) check). The intention is to stimulate better reusability by means of requirements on the manufacturer, so that as many batteries as possible proceed. The 'second life' batteries are considered new products and must also meet the requirements for the market for which they are intended. Customers should also have the opportunity to view documentation related to SOH or relevant testing as part of the technical documentation supplied with a recycled battery.

### Article 55

3. The collection target for portable batteries will be increased to 65% in 2025 or possibly 70% in 2030. The underlying idea is that a significant increase in collection will benefit the (cost) efficiency of the recycling and reuse processes.

### Article 61

4. New, improved reporting is foreseen for the collection of vehicle, EV and industrial batteries. The collection of batteries from light vehicles must be administered separately.

### Article 6, 56, 57 and Annex XII

5. The recycling and recovery of materials from batteries is subject to new targets. Lower limits are set for certain metals: 90% for cobalt, 90% for nickel, 35% for lithium and 90% for copper, in 2025. These ratios may be increased for 2030, based on technical feasibility at that time. The use of certain metals, in particular mercury and cadmium, is banned.

### Article 7 and Annex II

6. Industrial and EV batteries will be required to be accompanied by a carbon footprint declaration from 1 July 2024, based on a life cycle analysis according to a harmonized calculation method. In a second step, from 1 January 2026, there will be separate classes with limit values for the 'carbon footprint'. From 1 July 2027 there will be a lower limit for placing on the market.

### Article 10 and Annex IV

7. Industrial and EV batteries are required in the short term to be accompanied by information on, among other things, life and performance. This should enable customers to make substantiated choices. From January 1, 2026, minimum performance and sustainability requirements will be imposed, as well as a lower limit for marketing. The intention is that the market evolves automatically in this way towards batteries with a lower impact on the environment.

### Article 9 and Annex III

8. Non-rechargeable portable batteries are subject to minimum technical requirements regarding performance and durability.

### Article 8

9. There will be a mandatory declaration of the amount of recycled materials in industrial, EV and vehicle batteries. As with measures 6 and 7, this will be converted into a minimum requirement for 2030 and 2035.

### Articles 46 to 49. Article 49 deals specifically with vehicle, industrial and EV batteries.

10. Measure 10 aims to establish which responsibilities are placed with the manufacturers of industrial and EV batteries. This is a further refinement of the guidelines in the Battery Directive. Each battery manufacturer must register in a database in its Member State, so that compliance and collection requirements can be monitored. The responsibility, cost and practicalities of the collection thus still lie with the producer or a collective (referred to as Producer Responsibility Organisation, PRO).

### Article 11

11. Portable batteries are getting stricter requirements regarding the ability to remove and replace them. This should also improve the repairability and longevity of the devices in which they are built.

### Article 4, Article 13 and Annex VI, Article 60, Article 64 and 65, regarding the battery passport

12. There is a strong focus on the availability of information about each battery (so not just per type, but each one). To this end, batteries must be provided with harmonized labels by manufacturers including manufacturer, date of manufacture, battery type and chemistry, hazardous substances and critical raw materials. A QR code or link provides access to more extensive information online. This means that customers are better informed, which stimulates the market towards batteries that are less harmful to the environment. In addition, from January 1, 2026, there will be a (central) electronic system for industrial and EV batteries to make the above information accessible and to follow up: a “battery passport”. The latter should make battery reuse and recycling processes more efficient and safer. Repairs must also be kept in it.

### Article 14, 59 and Annex VII

13. Industrial and vehicle batteries must have a Battery Management System (BMS) that maintains information relevant to determining SOH and remaining life. This information must be accessible to the customer and parties who want to know the residual value of the battery and for reuse purposes.

Articles 70 to 72

14. The latter measure imposes “due diligence” with regard to the use and processing of raw materials required in the production of batteries.

Article 12 and Annex V are specifically about the safety of stationary storage systems.

Article 17, 18 and Annex VIII describe the procedures for conformity assessment of batteries.

15. There will also be more rules regarding the conformity and safety requirements of batteries. Batteries will need to be tested for thermal behaviour, short circuit, over and under charging, mechanical damage and other misuse. This is somewhat similar to what is already required of batteries for electric vehicles under the UN ECE R100.

## 5.2 CEN-CENELEC EM-CG - ADHOC GROUP BATTERIES

The European Commission has asked CEN-CENELEC (the European standardisation body) to develop standards for sustainable batteries. These standards must elaborate the requirements from the regulation. In October 2021 the standardisation request has been accepted by CEN-CENELEC. An ad-hoc working group has been established to develop the work programme. It is analysed if all topics and battery types from the legislation are covered by standards and if these standards are sufficient. The missing issues will be the basis of the work programme. The exigencies for repurposing batteries will be an important part of this programme.

## 5.3 IEC STANDARDS DEVELOPMENT

During the course of the CIRCUSOL project, work has started at international level (IEC) towards the development of second-life battery standards. Two working groups have been started at IEC TC21 (Secondary cells and batteries), for the preparation of the following standards:

- IEC 63330: Requirements for reuse of secondary batteries
- IEC 63338: General guidance for reuse of secondary cells and batteries

CEA and VITO are part of the working groups and actively contributing to the discussions.

### 5.3.1 IEC 63330 REQUIREMENTS FOR REPURPOSING OF SECONDARY BATTERIES

This standard is developed in the IEC Technical Committee 21. It mainly focuses on lithium batteries, but is not limited to them. Only redox flow batteries are excluded. The aim is to impose requirements on the reuse of batteries. Publication of the standard is foreseen around the end of 2023.

Insight into the possible content can be given but without certainty, since major modifications can still occur. **Figure 4** shows which stages in the production process are supported and which steps actors can focus on. These are indicated as '**a**' through '**k**'.

Data on the original (primary) use of the battery is needed:

Operating range data: datasheet values on temperature, voltage and current windows

Failure history data: If failures are detected, such as overload, the battery cannot be repurposed

Residual capacity data: measurement of actual capacity according to a standard

Data on usable period remaining at the end of primary use: Estimated usable period by the manufacturer of the primary battery minus the age of the battery. A product may not be repurposed after its lifespan.

Storage data: how the battery is stored after it has been taken out of its first life cycle, e.g. that it has not been dropped and stepped on.

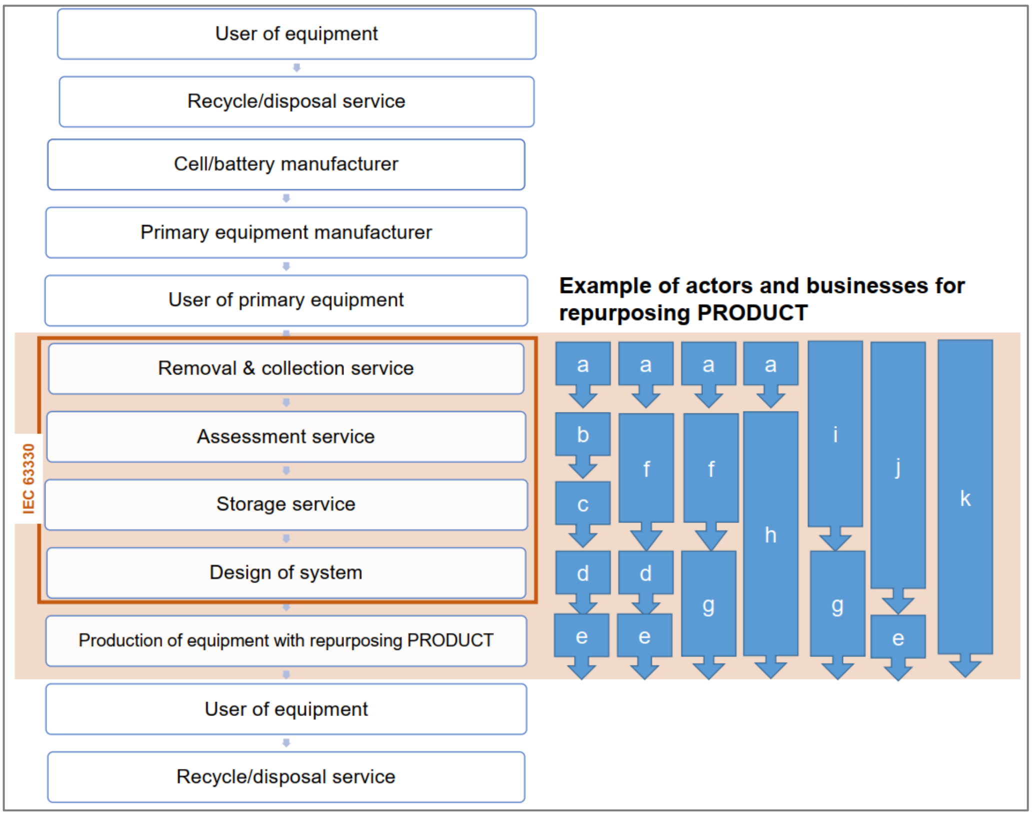


Figure 5: Production chain of a battery and which steps the standard applies to. Next to it is stated what kind of companies can participate. So there are 11 provided.

The standard provides a classification for the repurposing of batteries, taking into account their residual performance and useful life, see **Figure 5**. This gives classes from A1 to C3. Probably only the best batteries are interesting, or class A1, A2 and B1. Ultimately, this depends on the economic picture. The classes are related to hard criteria for classification. This is explained in the proposed test procedure in this report, i.e. Table 3.

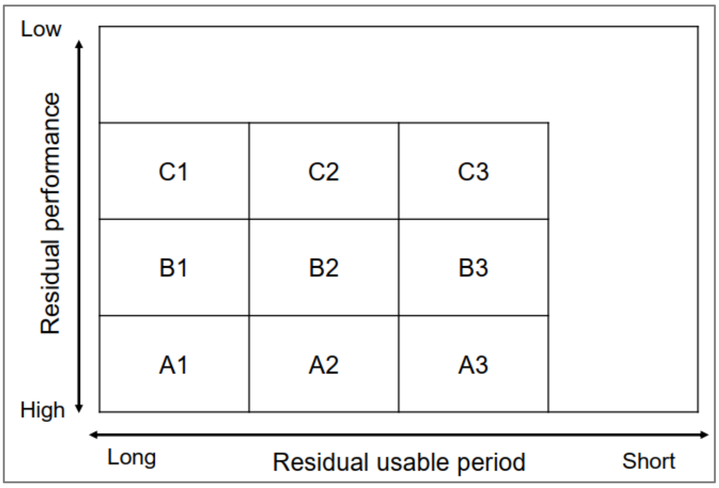


Figure 6: Repurposing classification as a function of remaining performance and period of use.

An explanation is given on whether or not to perform safety tests: if the battery is used within the estimated useful life of its primary use, and within the same operating range and operating environment, e.g. ambient temperature, humidity, dust, vibration, with a lower load than original, then the original design of safety and performance remains valid. An evaluation must be made of the changed system design and of the electrical safety in combination with the electrical installation. If the battery used is changed in system design (connections, cooling, BMS, contactors…), then the original safety design no longer applies. Safety must be proved by an evaluation of the new safety design required for the new use.

This standard seems less clear and concrete than UL1974.

### 5.3.2 IEC 63338 GENERAL GUIDANCE FOR REUSE OF SECONDARY CELLS AND BATTERIES

In parallel, subcommittee 21A initiated a request called “General guidance for reuse of secondary cells and batteries”, with a focus on lithium-ion and nickel-metal-hydride. The future standard should provide guidelines for reuse, ranging from environmental aspects, risks and coordination between the original manufacturer and the repurposing manufacturer.

This standard is intended to assist in the reuse of lithium and NiMH batteries, both for refurbishing (restoring a product and updating it) and repurposing (reuse in another application). A distinction is made between planned reuse and unforeseen. This standard under development has the 'CD' status at the beginning of 2021. This means that the national mirror committees can contribute to the present text. The standard currently provides a superficial description of how batteries work and what dangers there are (such as fire, and explosion). Cell-based reuse is not recommended because the desired conditions of use, especially with regard to functional safety, cannot be guaranteed. And also because their usage history cannot be tracked (at module level this may be stored in the BMS).

It is recommended that the BMS keeps the following data in its first life:

History of overcharge, over-discharge, overcurrent, external short circuit, the insulation value and/or insulation faults

History of excessive shock and vibration

The result of the BMS self-diagnosis

Error history concerns BMS communication with the application side

SOH

For the reuse of batteries, emphasis is placed on so-called battery lifetime traceability data. This concerns the same data as above regarding the BMS, supplemented with

Accidents

Storage conditions (such as period and environment).

It is emphasized that the safety of recycled batteries is lower because recycled modules have different usage histories. There are currently no non-destructive testing methods to make a statement about this. The destructive safety tests such as those with a new battery should take place under the prescribed conditions for the first application as well as the intended reuse application. Users should also be aware of the increased potential for hazards at the end of a battery's life. The originally planned operating range (such as voltage and temperature) should certainly not be expanded, but rather limited. If this area is expanded, it must be done with the application of the original battery manufacturer and the application of the standard on functional safety, IEC 61508.

Preferably, the original battery manufacturer provides a second life and indicates this on the batteries by means of the inscription: 'Before reusing this product, contractual agreement should be received from the original manufacturer'. If the manufacturer does not want reuse, it must put this on the battery via a lettering or bar or QR code. If battery life is specified, the battery should not be used for more than that period. This is not further specified. If reuse is prohibited, or no contract is concluded between the remanufacturer and the original manufacturer, the batteries should be recycled and the material preferably returned to new batteries.

# 6. SELECTION CRITERIA FOR REPURPOSING

Battery assessment is the core part of the labelling and certification protocol. The most important information for selecting the best suited application are discussed in this section, in particular cell resistance, cell capacity and the homogeneity of the cells within cell blocks, modules and the complete battery. CEA and VITO have worked on the development of diagnosis methods for a reliable estimation of these values.

## 6.1 DEFINITION OF SOH AND SOC

The terms State-of-charge and State-of-health are commonly used with batteries to indicate the current charge or condition of the battery. However, these are ambiguous numbers that need to be viewed in context.

### 6.1.1 STATE OF CHARGE (SOC)

Practically every application with batteries needs an estimate of the remaining energy content. In an EV, the SOC replaces the traditional fuel gauge and serves as input for the calculation of the remaining driving range. For a stationary storage system that provides services to the electricity grid, it is used for planning energy transactions. In general, the State-of-Charge of a battery can be defined as the ratio of the current charge $(Q_{\text{actual},t})$ to the nominal $(Q_{\text{nominal}})$:

$$SOC = \frac{Q_{\text{actual},t}}{Q_{\text{nominal},t}}$$

However, the SOC cannot be measured directly, and its calculation and interpretation is not obvious. More definitions will follow later in this chapter.

NOMINAL CAPACITY

To begin with, the total usable energy capacity of the battery, $Q_{\text{nominal},t}$, must be known as a reference value. For a new cell (t=0) this value can be taken directly from the manufacturer's datasheet and specified there for a constant discharge current between maximum and minimum voltage limits (the cutoff voltage). The discharge rate used in the datasheet usually depends on specific application standards: C/3 (a three-hour discharge) for EV application; C/5 (a five-hour discharge) for portable applications.

At higher discharge currents, there is a stronger voltage drop due to the internal resistance of the cells. As a result, the cut-off voltage is reached faster and the nominal capacity is not reached. This is illustrated in Figure 7, where the cell (or battery) voltage is shown as a function of the discharge capacity. At higher currents (2C for example) the capacity is lower (e.g. 75% instead of 100%) than at moderate currents (0.5C in this case).

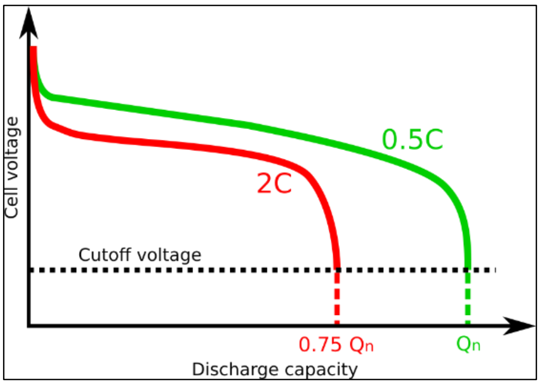


Figure 7: Higher discharge currents lead to lower discharge capacities.

DETERMINING SOC

There are several SOC methods to determine the actual energy level in a battery in a real application. We can distinguish between three approaches:

Direct measurements assume the relationship between the open-circuit voltage (OCV, more detail in section 6.4) of the battery and the SOC. Unlike lead-acid batteries, lithium batteries have a strong non-linear SOC-OCV relationship. Different lithium chemistries also have a different curve. Temperature will also affect that, and some chemistries also exhibit hysteresis effects, with the OCV at rest after charging being different than after discharging for an equal SOC level.

Integration or bookkeeping methods are based on the integration of the current flowing into or out of the battery. Hence, it is also called Coulomb counting and its accuracy is highly dependent on the current measurement and charging efficiency of the cell chemistry. Qualitative sensors can have 0.5% measurement error at their rated current, and that error slowly builds up in the calculated SOC through integration. In order to keep them usable over a longer period of time, integration methods have to compensate for the 'drift' and/or reset regularly (for example when fully charged).

More advanced algorithms are based on a combination of techniques and filtering. A common approach is based on the Kalman filter. The filter combines voltage and current measurements with a battery model to derive the most likely SOC.

### 6.1.2 STATE OF HEALTH (SOH)

The term State-of-Health is commonly used when describing the 'health' or degradation of the battery. However, different applications place different demands on a battery, which can make SOH ambiguous. A portable device that draws a small, stable current from a battery can survive for a very long time on 1 charge: the energy density takes precedence. In another application, for example a cordless drill driver, the battery has to be able to supply large peak currents or peak powers for a short time: the power density takes precedence. The interpretation of 'health' will therefore be related to the application context.

The degradation of a battery can generally be broken down into two aspects: calendar aging and cyclic aging. Calendar aging has to do with the consequences of battery storage, while cyclic aging is related to the (cyclic) charge/discharge patterns of its use. Degradation will manifest as a decreasing energy density or as a lack of power when delivering short pulses of power. Both effects have different causes and can evolve independently of each other, making a battery unusable for an application but still acceptable in another.

This means that SOH can be defined according to different characteristics. The most commonly used are:

Based on the (energy) capacity in Ah and Wh (section 6.3)

Based on peak power (W), or internal resistance (mΩ) or impedance (section 6.5 and 6.6)

Based on self-discharge (section 6.7)

For lithium batteries, self-discharge is very limited. The effect is usually caused by the coupled electronics (BMS) taking a small current from the cells to function.
Micro-perforations, created by dendrites through the separator of battery cells, can also cause small current paths that lead to self-discharge. Thus, problematic cells can be identified.

## 6.2 RISKS AND AGEING FOR LI-ION CELLS

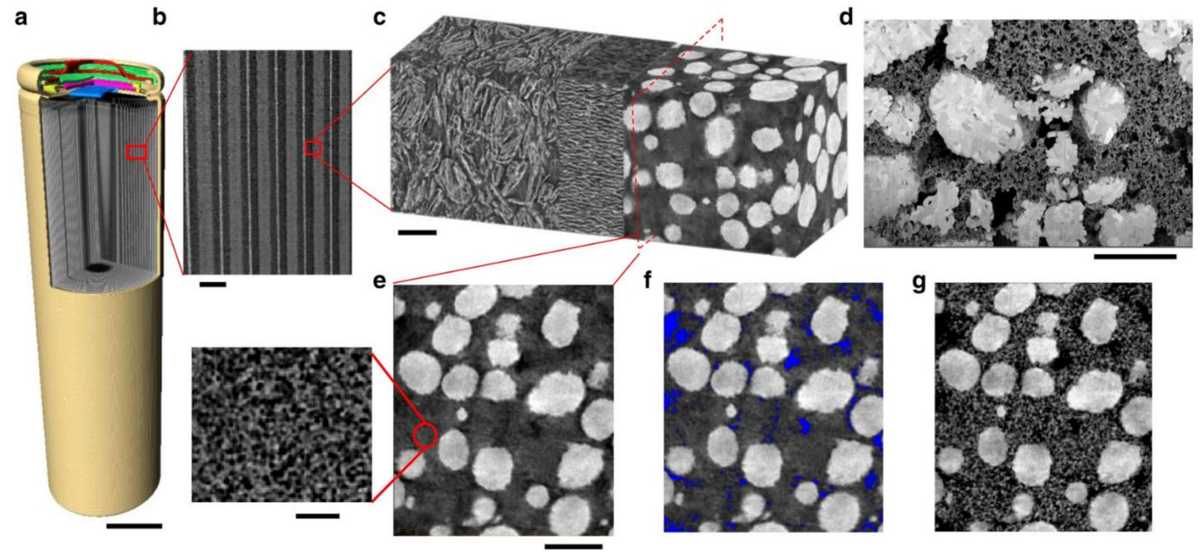
### 6.2.1 LI-ION CELL CONSTRUCTION

To discuss the aging of Li-ion cells, it is first necessary to understand how a Li-ion cell is constructed.

The anode is applied on a coated copper layer. It consists of graphite particles (the active material or particles) with an electrolyte in between for ionic conduction and carbon chains for electrical conduction. There is also a binder, usually PVDF, to hold the particles together and provide mechanical strength. Additional substances are added to suppress aging, for example by reacting with gaseous substances (especially HF) that can be released. More and more, a small percentage of silicon particles is added to the anode. This increases the capacity. The electrolyte and the graphite do not mix: the organic solvents react with the graphite. Fortunately, this forms a stable layer: the solid electrolyte interface (SEI). An analogy is the oxidation layer on metals. After that, the electrolyte no longer touches the graphite and a stable state is created.

At the cathode there is a similar composition but the active particles consist of a cobalt-based material or of iron phosphate. These particles are usually coated. The coating can serve to improve current conductivity with iron phosphate and for electrolyte resistance in low cobalt NMC materials. The cathode is applied on an aluminium layer, which is also coated. Between the cathode and anode is a separator, usually a microperforated polyethylene layer, which itself consists of several layers. The separator prevents electrons to pass whereas the ions can flow through, preventing in this way a possible short circuit. A ceramic layer may also be provided in the separator for better strength against dendrites.

A recent study measured the electrode structure using X-ray technology. This is shown in Figure 8. So it is almost a solid layer of compressed substances. It's just not solid but a little porous to the electrolyte. An artistic sketch in Figure 9 shows how the ion conduction and electron conduction takes place in the electrode.



**a** Volume rendering of the reconstructed cylindrical battery scanned by X-ray micro-CT (accelerating voltage 180 kV, exposure time 1 s and voxel size 12.9 µm). The metal shell (brown), top button (red), venting disk (green), crimp plate (pink), seal insulator (yellow) and current collector (blue) are shown, with a corner cut displaying the internal structure of the battery; **b** magnified virtual slice to show the periodic layered structure of the cell; **c** X-ray nano-CT image showing (from left to right) the graphite anode, polyolefin separator and NMC cathode; **d** SEM image showing the CBD morphology alongside the secondary NMC particles, wherein the crystallography of the primary particles is seen; **e** virtual slice of the reconstructed 3D electrode, showing a blurry phase comprising the CBD and micro-pores (white: active material particles; dark grey: macro-pores; light grey: blurry mixed phase of micro-pores and CBD). Inset image shows the higher resolution scan of the CBD phase; **f** macro-pores (blue) are highlighted and retained with the active particle in the dual-scan superimposition process; **g** the resultant full microstructure of the NMC cathode by X-ray CT. The scale bars in (**a**, **b**) represent 10 mm and 240 µm respectively, 10 µm in (**c**, **d**, **e**) and 2 µm in the inset of (**e**).

Figure 8: Microstructure of a Li-ion electrode (CBD stands for carbon-binder domain, so the binding material and the electron conduction). [18]

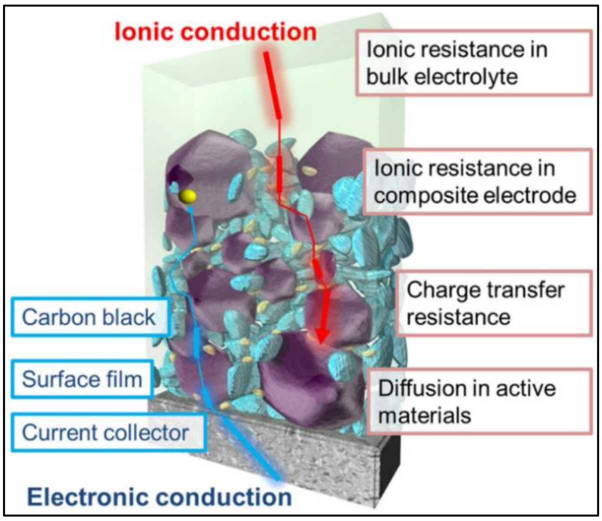


Figure 9: Construction of an electrode clearly showing how the charge, in the form of electrons and ions, can move [19]

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[18] X.Lu e.a., ‘3D microstructure design of lithium-ion battery electrodes assisted by X-ray nano-computed tomography and modelling’, Nature Communications volume 11, Article number: 2079 (2020); https://www.nature.com/articles/s41467-020-15811-x/figures/1

[19] Y.Orikasa e.a., , Ionic Conduction in Lithium Ion Battery Composite Electrode Governs Cross-sectional Reaction Distribution’, Nature Scientific Reports, 2016; https://www.researchgate.net/figure/Schematic-illustration-of-a-composite-electrode-in-lithium-ion-batteries_fig1_303392583

### 6.2.2 AGING MECHANISMS

The aging of a battery is fundamentally related to the change of the material's characteristics over time and during use. Essential characteristics of a battery are its available energy and power, along with its mechanical integrity (dimensions, leaks…). As discussed earlier, aging is usually expressed as capacity or power versus number of cycles, total throughput (the total amount of energy passed through the battery), or time since commissioning.

The degradation of performance is a result of a number of aging mechanisms, which in turn are determined by the conditions of use. In some cases, especially when the battery is used under extreme conditions, it is possible to attribute the loss in capacity or power to a specific mechanism or process. A summary of the major electrode aging mechanisms is shown in Figure 10, Figure 11 and Figure 12. The aging mechanisms can be classified according to mechanical changes (particle cracking, gas evolution), surface film formation (SEI & lithium plating), bulk material changes (structural disordering) and parasitic reactions (binder degradation, localized corrosion). Under 'ideal' conditions, these are the degradation mechanisms that age a lithium cell. In reality, other degradation mechanisms will also affect the capacity decline and cause additional cell aging.

In general, therefore, the decline in capacity is due to three processes:

Loss of lithium, causing an imbalance between the electrodes.

Loss of active electrode surface.

Loss of electrode material and loss of electrical and ionic conductivity.

The capacity loss includes reversible and irreversible parts. The reversible part is called self-discharge and can be recovered by charging the battery. The irreversible part is due to the degradation and cannot be repaired.

Assuming that the different inert components (binders, separator, current collector) are correctly selected for their chemical and electrochemical stability with the active materials and the electrolyte (which is crucial in the design phase), it is mainly the interaction between active materials and the electrolyte that is responsible for the aging during storage of the cell (calendar aging), and the thermodynamic stability responsible for the aging.

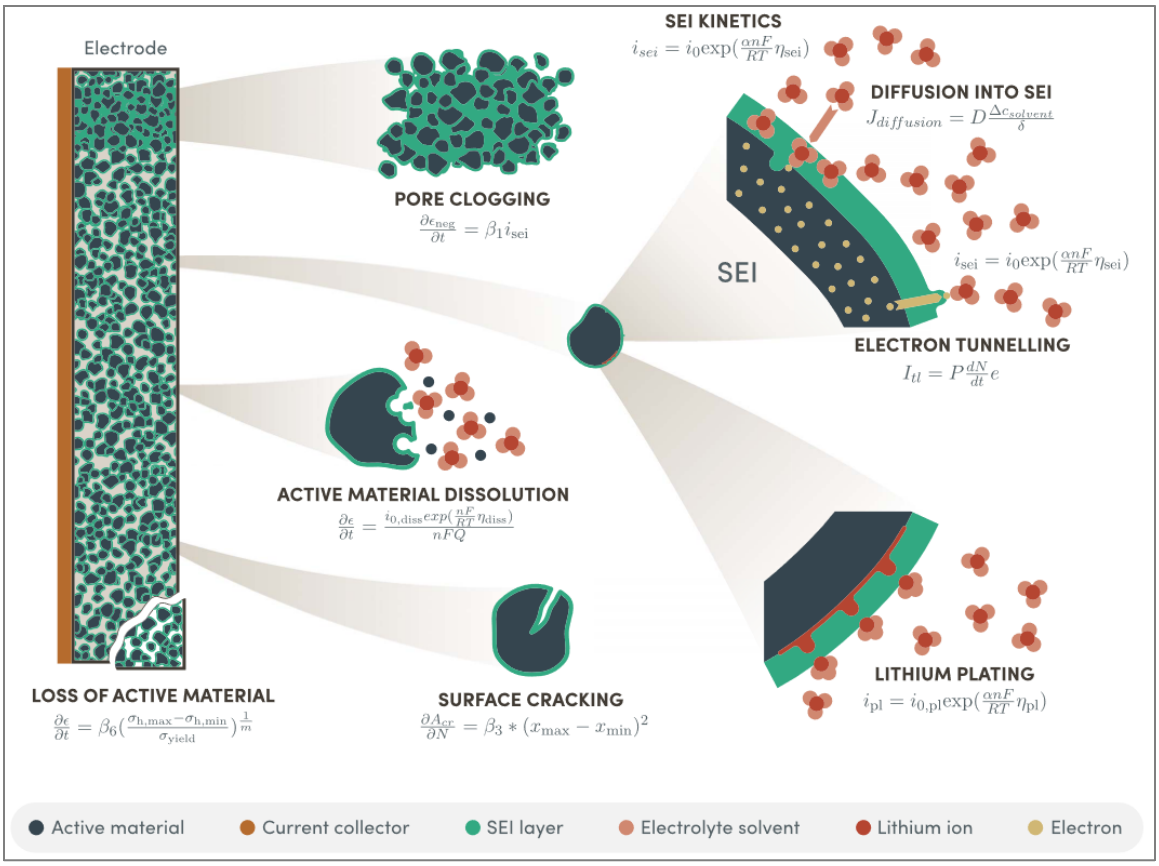

Figure 10: Degradation mechanisms in lithium batteries[20]

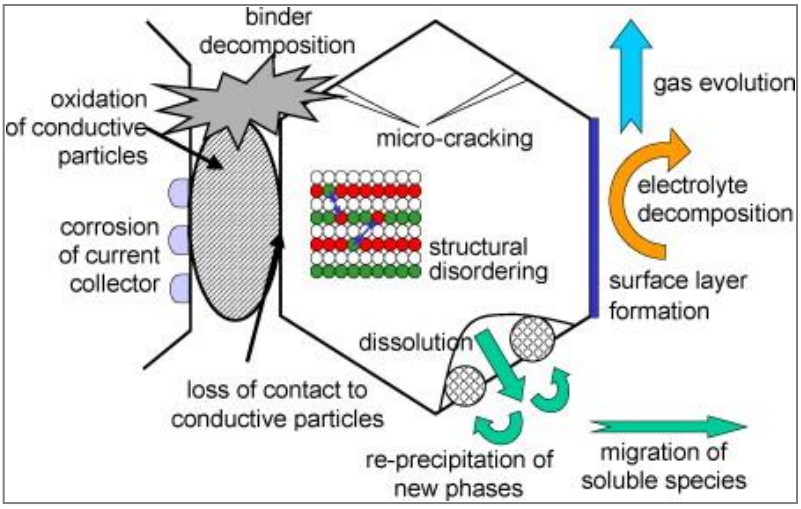

Figure 11: Overview of the main aging mechanisms of the cathode materials[21]

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[20] Review and Performance Comparison of Mechanical-Chemical Degradation Models for Lithium-Ion Batteries. J.M. Reniers, G. Mulder, D.A. Howey, Journal of the Electrochemical Society 166, 2019, pages A3189-A3200, http://dx.doi.org/10.1149/2.0281914jes

[21] Wei He et al, "Challenges and Recent Advances in High Capacity Li-Rich Cathode Materials for High Energy Density Lithium-Ion Batteries", Advanced Materials, March 2021, https://doi.org/10.1002/adma.202005937

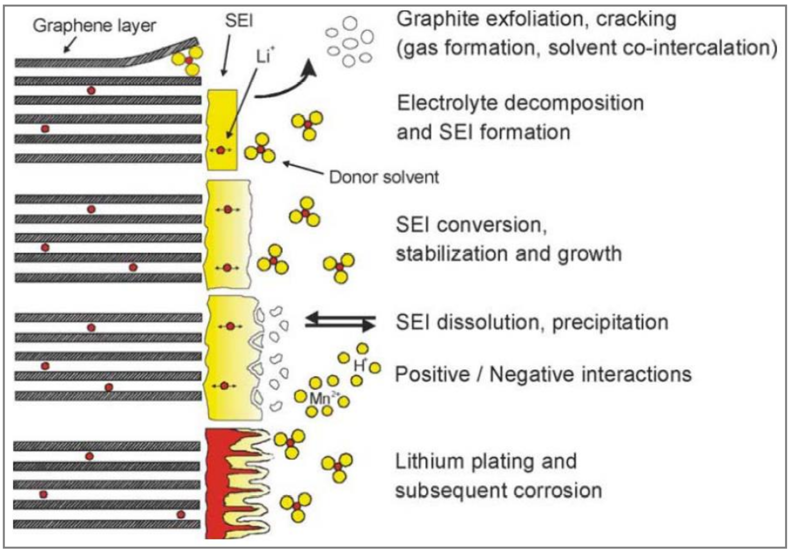

Figure 12: Changes to the anode/electrolyte interface[22]

Schematically capacity degradation through cycling goes through four phases (**Figure 13**). The first degradation phase, A on the figure, goes quickly but does not last long. This is followed by two 'slower' phases, referred to as B and C. Finally, there is phase D, which goes fast and announces the end of the cell. The different rates can be attributed to separate changes in the cell, and are described in the next section.

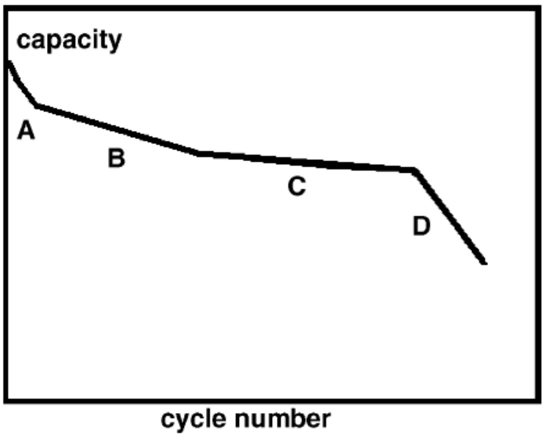

Figure 13: Schematic evolution of capacity degradation over time

- **Phase 1:** The rapid decrease in capacitance in the first phase can be explained by the loss of lithium ions during the formation of the Solid Electrolyte Interphase (SEI), a thin layer of a few nanometers on the anode. This side reaction will gradually slow down as the cell is used because the growing SEI layer on the anode prevents its further formation.
- **Phase 2:** In the second phase, it is the anode that determines the degradation rate. Due to the presence of a stable SEI layer on the anode, less active material is available, so that fewer lithium ions can intercalate in the anode (see also **Figure 12**) during charging. Due to the continuous charging and discharging, the SEI layer will crack

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[22] J. Vetter et al., “Ageing mechanisms in lithium-ion batteries,” Journal of Power Sources, vol. 147, no. 1-2, pp. 269-281, Sep. 2005

more and more and expose active material again. This results in more side reactions, the SEI layer grows and becomes less porous, and more lithium ions are lost.

- **Phase 3:** In the third phase, the degradation rate of the active cathode material will exceed the loss of the lithium ions. A layer similar to the SEI layer, called Solid Permeable Interphase (SPI) also forms on the interface between cathode and electrolyte (see also **Figure 11**). This layer also grows through charging and discharging and eventually limits the available amount of active cathode material. Note that in stage 3, the anode is still the limiting electrode, as there is still more active cathode material available than lithium ions.
- **Phase 4:** Due to the strong degradation of the cathode in the 4th phase, it becomes the limiting electrode. Less cathode material is then available than lithium ions. I.e. that not all lithium ions intercalated in the anode during charging are intercalated in the cathode during discharging. More and more lithium ions thus remain trapped in the anode, while the cathode is completely intercalated during discharge. This results in an accelerated capacity decrease in the fourth phase.

According to several studies, the degradation of the capacity is mainly due to the side reaction that takes place at the interface of active particles and the electrolyte, while the properties of the bulk material in anode and cathode does not change much during the life of a cell. This mechanism takes place during charging and discharging as well as during storage (calendar aging).

The cycling of a cell involves a change in volume of the active particles (such as the graphite spheres) which changes the interface with the electrolyte, thereby stimulating processes at that interface, such as the formation of a passive layer. Cracks can also form through the active particles. Contact with the electrolyte immediately causes new growth of an SEI layer. On the other hand, it is possible that storage at a high SOC induces stronger aging than charging and discharging because the materials are continuously maintained at their highest state of reactivity.

The most common aging phenomena are the following:

**SEI layer formation:** The SEI layer plays a vital role in protecting the graphite electrode from co-intercalation of solvents that are part of the electrolyte. However, the layer also causes an irreversible loss of capacity during the initial charge and discharge cycles. The ideal SEI layer is therefore uniform, thin, and allows lithium ions to pass through but functions as an insulator for the electrolyte.

**Lithium plating:** Under normal operating conditions, a lithium cell does not contain metallic lithium. However, under aggressive charging conditions, lithium that was not intercalated into the graphite (because all free spots are occupied and intercalation is a slow process) can precipitate on the graphite anode. This can pose problems for the performance, reliability and safety of the cell. Lithium plating is most pronounced at low temperatures and/or (very) high charging currents. In extreme situations, a significant amount of lithium can precipitate irreversibly in just a few cycles. Plating is rarely included in aging models.

**Gas Formation:** Some parasitic reactions in the cell can lead to the formation of gas. At high temperatures, the decomposition of the electrolyte becomes a safety risk (thermal runaway and explosion, overpressure…) The gas formation creates mechanical stress on the electrodes, which promotes the formation of SEI and in the worst case leads to rupture of the cell housing. Gas trapped in the pores of the porous electrodes also reduces their active surface area.

**Delamination:** The expansion and contraction of the electrode, which is responsible for the growth of the SEI layer, can also have other negative effects. If the expansion is strong enough to break the bond between electrode and current collector, so-called delamination occurs. The current collector is the substrate on which the electrode material is applied and provides a path for the current to enter and exit the cell. The current collector itself does not expand or contract, creating mechanical stress at the interface with the anode. When delamination occurs there is less contact area, which increases the internal resistance and increases the current density on the remaining surface.

**Dendrite Formation:** Instead of precipitating as a flat surface, lithium can also form dendrites. The same is true for copper which may have been in solution if the cell voltage falls below 1.5 V for several days. These rods can pierce the separator and cause a tiny internal short circuit. This usually destroys the dendrites themselves, but it can also lead to a thermal runaway of the cell.

### 6.2.3 RISKS

OVER-DISCHARGE

Lithium cells with a graphite anode are highly sensitive to over-discharge. Once the cell voltage falls below 1.5V, the copper of the anode can start to dissolve and later during charging promote the precipitation of lithium metal in a needle-like structure (dendrites). In extreme cases, this leads to an internal short circuit and thermal runaway[23]. Therefore, lithium batteries should always be used with a safety device such as a BMS.

OVERCHARGE

Overcharging lithium cells can lead to instant danger. Lithium battery cells do not have a safe side reaction that safely converts the excess energy into heat while the voltage cannot continue to rise freely. This is precisely the case with NiMH and lead-acid battery cells. Because the voltage rises during overcharging and thus moves outside the stable range of the electrolyte, this will give rise to gas with pressure build-up. Cylindrical and prismatic cells have specific sites to divert that pressure out. A pouch cell will swell and burst. It is important that there is no fire or explosion. Prior to allowing their commercialisation, all battery cells are tested for this. Nevertheless, this danger cannot be ruled out. To this end, a safety device is required to detect overcharging in time and to reduce or stop the charging current.

## 6.3 CHARGE AND DISCHARGE CAPACITY

The most commonly used definition of SOH is based on a battery's ability to store energy. So we can express the SOH as the actual capacity in Ah of the battery $Q_{\text{actual}}$) versus the capacity of the battery when it was new $Q_{\text{initial}}$):

$$SOH_{cap,1} = \frac{Q_{\text{actual}}}{Q_{\text{initial}}}$$

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[23] H.Maleki, 'Effects of overdischarge on performance and thermal stability of a Li-ion cell', Journal of Power Sources 160, 2006, p. 1395-1402; https://doi.org/10.1016/j.jpowsour.2006.03.043

To determine whether a battery is end-of-life, that means end-of-*first* life, EV applications typically use a capacity limit of 80%, equivalent to $SOH_{cap,1} = 80\%$. Once the capacity drops below this limit, the battery may still be useful in a second-life application where power density is less important. It is also possible to express SOH relative to the 80% limit:

$$SOH_{cap,2} = \frac{Q_{\text{actual}} - 0.8 * Q_{\text{initial}}}{0.2 * Q_{\text{initial}}}$$

In this case, the SOH will be equal to 0% when the battery capacity has dropped to 80% of its original value.

As with the SOC, a reference value of the capacity is required. The value can be taken from the manufacturer's datasheet for a new cell, between fixed voltage limits, at a fixed discharge current and at a certain temperature. Thus, $Q_{\text{initial}}$ refers to the initial capacitance under nominal test conditions. That is, using the same battery in less demanding applications can yield an SOH above 100%. To avoid confusion in comparison, the actual capacitance $Q_{\text{actual}}$ must therefore be determined under the same nominal test conditions that apply to $Q_{\text{initial}}$. This can be done by performing a controlled charge-discharge-charge test. Strictly speaking, its test conditions are difficult to reproduce outside of a lab environment, yet this test will provide an accurate picture of its condition. The disadvantage is the relatively long time it takes. Larger cells or batteries also require specialized test equipment that can handle the high voltages and/or currents.

## 6.4 OPEN CIRCUIT VOLTAGE

The Open Circuit Voltage is the voltage applied to the terminals of a cell or battery when no load is connected, and thus no current flows in or out of the battery. The open-circuit voltage depends, among other things, on the type of battery (lead-acid, lithium iron phosphate (LFP), lithium-nickel-manganese-cobalt (NMC), …), the state of charge (SOC), temperature, but also the rest time after a previous charge - or discharge action.

| Battery type | Discharged | Fully charged | Average |
|---|---|---|---|
| Lead acid (PbAc) | 1,8 V | 2,1 V | 2,0 V |
| Lithium iron phosphate (LFP) | 2,5 V | 3,65 V | 3,2 V |
| Lithium nickel-manganese-cobalt-oxide (NMC) | 2,7 V | 4,2 V | 3,6 V |
| Lithium titanate (LTO) | 1,8 V | 2,7 V | 2,3 V |

Table 1: Typical battery voltages

As stated in 6.1, cell manufacturers guarantee a certain nominal capacity between specified voltage limits. Similar limits exist for extreme usage and storage conditions. If a cell is used outside these voltage limits, this can have consequences for aging (SOH) and safety.

A test on the minimum voltage of incoming batteries or cells thus allows to quickly identify unsuitable ones. Although it is in principle possible to gently recharge cells that are at too low a voltage, a certain internal degradation is inevitable, making it economically unprofitable to reuse them and probably dangerous.

## 6.5 INTERNAL RESISTANCE

Another method of expressing the SOH is based on the ability to deliver power. The response of a battery to the connection of a load is related to its internal resistance and impedance.

The maximum current that can flow into and out of a battery is related to the voltage limits. As mentioned earlier when discussing the nominal capacity, higher discharge currents will cause a larger voltage drop across the internal resistance. If that voltage drop is sufficiently large, the cut-off voltage is reached. At that point, the current cannot increase without exceeding the operating conditions imposed by the manufacturer.

Over the life of a battery or cell, its internal resistance will increase. The SOH can be expressed as the ratio of the internal resistance to its original value.

$$SOH_{Ri,1} = \frac{R_{\mathrm{i,initial}}}{R_{\mathrm{i,actual}}}$$

It is common to consider a cell to be end-of-life if its internal resistance is doubled, which corresponds to $SOH_{Ri,1} = 50\%$. As with the capacity-based SOH, it can also be expressed relatively:

$$SOH_{Ri,2} = \frac{2R_{\mathrm{i,initial}} - R_{\mathrm{i,actual}}}{R_{\mathrm{i,initial}}}$$

Measuring internal resistance is relatively simple, but can be done in many ways.

Incidentally, the resistance values between dissimilar battery cells cannot simply be compared. A large battery has a much smaller resistance than a small one, even though it consists of the same structure and materials: the resistance is inversely proportional to the capacity. The well-known cylindrical Li-ion cells with a capacity around 3 Ah will have a DC resistance in the vicinity of 40 mΩ, while a prismatic cell with a 15 Ah capacity will have a DC resistance of around 5 mΩ. To compare batteries, the resistance should be multiplied by the capacity. This is shown in Figure 14. The measurement methods used (DC and AC) are explained in the following subsections.

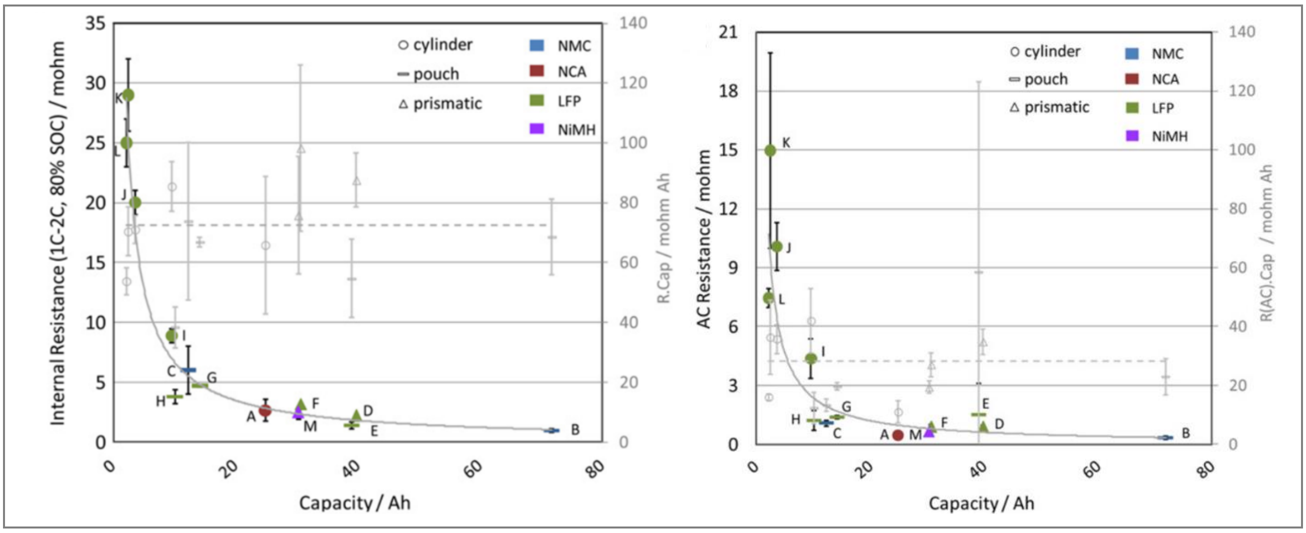

Figure 14: The resistance of a battery cell turns out to be inversely proportional to its capacity. Therefore, to compare cells, resistance must be multiplied by capacitance (the gray data in the figures).[24]

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[24] G.Mulder e.a., 'Comparison of commercial battery cells in relation to material properties', Electrochimica Acta,Volume 87, 2013, pages 473-488; http://dx.doi.org/10.1016/j.electacta.2012.09.042

### 6.5.1 DC RESISTANCE

In essence, a current step is imposed on the cell or battery and the voltage response is measured. It is a commonly used method, but the result depends on a number of internal and external factors:

Size and direction of the current step

Actual charge level (SOC) of the cells or battery

Voltage response measurement interval

Temperature

For illustration, Figure 15 shows the response of a cell to a current step, $I_{\text{step}}$.

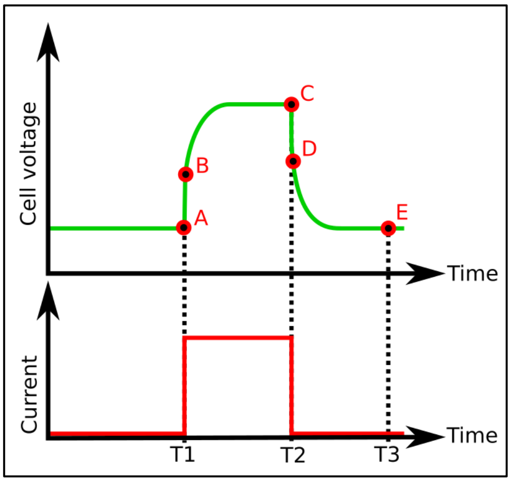


Figure 15: Current step response of a cell

In the case of a charging current, the resulting internal resistance $R_{i,\,\text{chg}}$ can be defined as:

$$R_{i,\,\text{chg}}(SOC, T) = \frac{V_B - V_A}{I_{\text{step}}}$$

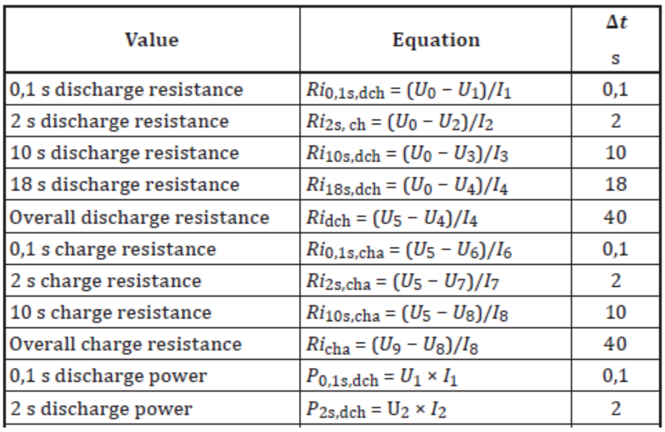
or alternatively:

$$R_{i,\,\text{chg}}(SOC, T) = \frac{V_C - V_A}{I_{\text{step}}}$$

where $V_A$is the voltage at time $T_1$ and $V_B$is the voltage immediately after application of the current. $V_C$ is the cell voltage after for example 1, 5 or 10 seconds.

The later the voltage $V_C$ is measured, the greater the proportion of the polarization resistance (the voltage difference B→C, similar to relaxation at open-circuit voltage) in the calculated value of the internal resistance. It is therefore important to consider the test method when determining an SOH value. The outcome is only comparable with a new battery or cell if the conditions and parameters are comparable (time step, SOC, charge/discharge but also temperature and current).

Some standards prescribe a stepped current as the measurement method, such as IEC 61951-1 and -2 for NiCd and NiMH batteries. Others have a clear indication at which points the voltage should be measured. For example, ISO 12405-4[25] assumes 100 ms sample time, as shown in Figure 16.



| Value | Equation | $\Delta t$<br>s |
|---|---|---|
| 0,1 s discharge resistance | $Ri_{0,1s,dch} = (U_0 - U_1)/I_1$ | 0,1 |
| 2 s discharge resistance | $Ri_{2s,\,ch} = (U_0 - U_2)/I_2$ | 2 |
| 10 s discharge resistance | $Ri_{10s,dch} = (U_0 - U_3)/I_3$ | 10 |
| 18 s discharge resistance | $Ri_{18s,dch} = (U_0 - U_4)/I_4$ | 18 |
| Overall discharge resistance | $Ri_{dch} = (U_5 - U_4)/I_4$ | 40 |
| 0,1 s charge resistance | $Ri_{0,1s,cha} = (U_5 - U_6)/I_6$ | 0,1 |
| 2 s charge resistance | $Ri_{2s,cha} = (U_5 - U_7)/I_7$ | 2 |
| 10 s charge resistance | $Ri_{10s,cha} = (U_5 - U_8)/I_8$ | 10 |
| Overall charge resistance | $Ri_{cha} = (U_9 - U_8)/I_8$ | 40 |
| 0,1 s discharge power | $P_{0,1s,dch} = U_1 \times I_1$ | 0,1 |
| 2 s discharge power | $P_{2s,dch} = U_2 \times I_2$ | 2 |

Figure 16: Example of the test points for the calculation of the internal resistance from ISO12405-4

### 6.5.2 AC RESISTANCE

Another (complementary) way to determine the internal resistance is by applying an AC signal. By changing the frequency of this signal, different aspects of the internal resistance can be derived (which actually becomes an impedance measurement, see also section 6.6). The most common AC resistance measurements are made with a 1 kHz signal. Unlike the DC method, the AC method also yields a phase angle ϕ. Not all devices measure this.

$$Z = \frac{U(t)}{I(t)} = \frac{U_{\max} e^{i(\omega t+\varphi_U)}}{I_{\max} e^{i(\omega t+\varphi_I)}}$$

However, the resulting value for the impedance Z strongly depends on the frequency and on the measuring device used.

## 6.6 ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY (EIS)

Electrochemical Impedance Spectroscopy (EIS), is an extension of the AC resistance method: the impedance is measured over a frequency range, usually between 10 mHz and 5 kHz. The measurement result is displayed as a Nyquist plot. That is, the imaginary resistance against the real resistance. It was already explained under section 6.5 that the DC resistance is directly dependent on the capacity. That remains the case here as well. Now you can also look at the shape of the plots. It turns out that these shapes look quite different between batteries, even if only Li-ion batteries are measured. This is visible in Figure 17.

The impedance characteristic provides insight into the internal behaviour of the battery cell. The left image in Figure 17 is the simplest situation. There is an inductive part at high frequency. The graph here lies below the X-axis and goes steeply downwards (the imaginary resistance is then positive: the graph shows the negative

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[25] ISO 12405-4:2018, Electrically propelled road vehicles —Test specification for lithium-ion traction battery packs and systems — Part 4: Performance testing, https://www.iso.org/standard/71407.html

resistance (-Im(Z)). There is a semicircle visible and a linear tail towards the top right. This is the direction where the frequency gets progressively lower.

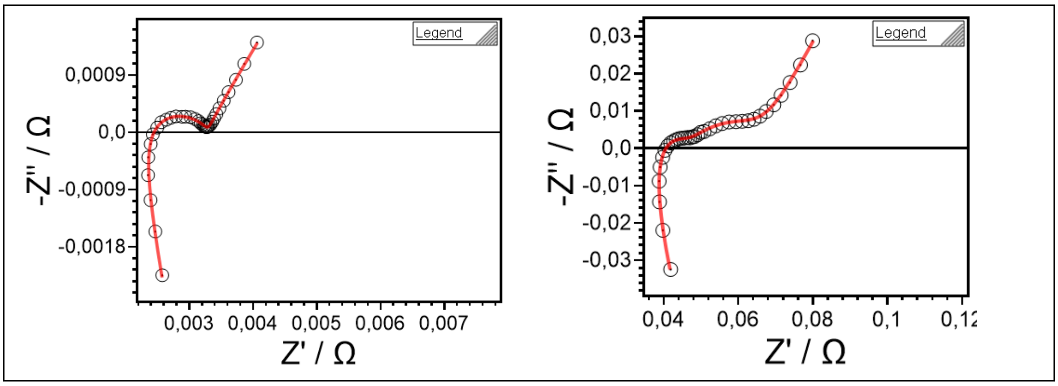

Figure 17: Two impedance characteristics measured on different, fully charged, Li-ion cells. The representation is the Nyquist plot. (source: VITO measurements).

The frequency where the graph goes below the X-axis is between 200 Hz and 3 kHz and is battery dependent. This intersection with the real axis is attributed to the sum of the resistance contributions from the electrolyte, the contact resistance between the porous electrodes and the current collectors, and the external circuitry and connections. The latter may vary if a different arrangement, including the cell holder and cable connections, is used. The resistance of the semicircle, or its width, is attributed to fast interfacial phenomena such as charge transfer, while the resistance in the tail is dominated by the solid state diffusion.

The same influences that applied to the resistance values apply here again: the impedance depends on temperature, SOC and SOH. In order to follow the aging, the other conditions must therefore remain completely the same. Fortunately, that is doable while reversing aging is not. This is shown in Figure 18 for an arbitrary Li-ion cell. Unfortunately, the axes do not have equal values, so that the difference would be graphically clear. The imaginary part of the resistance has increased tenfold while the real part has roughly doubled. After aging, the semicircle is preceded by a kind of kink. This indicates a new resistance contribution in the interfacial phenomena.

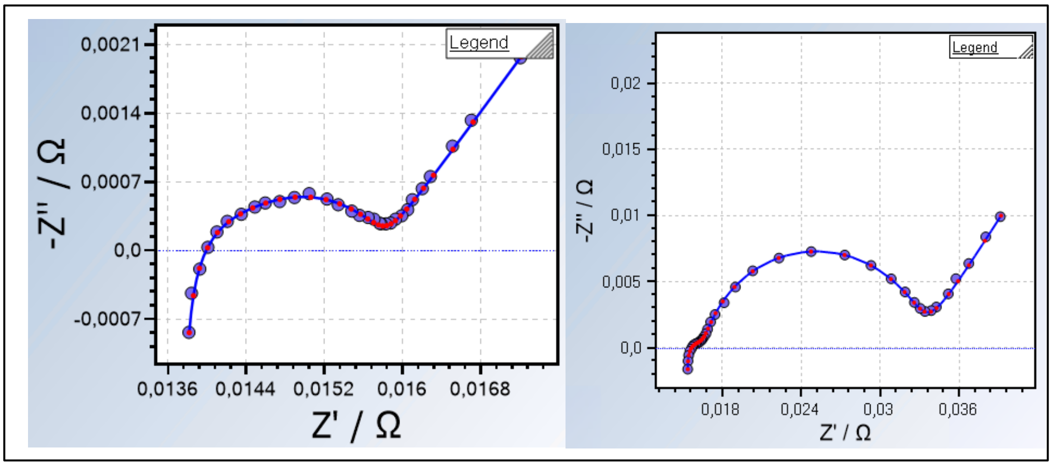

Figure 18: Nyquist plots of a Li-ion cell: on the left in new condition and on the right in aged condition (source: measurement data VITO).

## 6.7 SELF-DISCHARGE

A characteristic of most batteries is that they suffer from self-discharge, or leakage current, to varying degrees. Self-discharge is a continuous process that discharges the cell very slowly, independent of the connected load. The extent depends on the cell chemistry, the SOC, temperature and capacity, but also on variations in production. Small button cells (100 mAh) can self-discharge in the order of micro-amperes while large cells of 60 Ah and above can go in the direction of 0.5 mA. A rule of thumb is a loss of less than 2 % of the charge over 1 month.

Its cause is not fully known, but is usually attributed to parasitic reactions between the active materials and the electrolyte[26], see section 6.2.

Knowing the self-discharge of the cells is especially important in the design of the battery. For devices where the battery is at rest for a long time (e.g. pacemakers; 5-15 years) it is a necessary element to know the time to replacement. It is also a factor in determining the balancing options for the design of a BMS. A greater-than-average self-discharge of a few cells or widely differing self-discharge values can give rise to difficult-to-balance modules (and excessive balancing actions by the BMS). Therefore, modules are usually composed of cells of the same batch.

A higher-than-normal self-discharge may also indicate a cell with manufacturing defects or severe degradation, for example from exposure to high temperatures.

### 6.7.1 DELTA OCV APPROACH

The simplest way to measure self-discharge is via the open-circuit voltage of the cell[27]. The open-circuit voltage of a cell that has come to a complete rest is measured. The SOC corresponding to that voltage is tracked. The cell is then stored at a stable temperature and measured again after a certain time. The SOC at that time can be compared with that at the start of the test. The difference in mV is thus converted into a mAh value via the OCV-SOC relationship, and after dividing by the elapsed time, the self-discharge in milliamps is obtained.
The challenges with this method are correctly estimating the 'relaxation', the accuracy of the voltage measurement and keeping the temperature stable.

The relaxation is the time during which the voltage of the cell stabilizes. During the first minutes after charging or discharging, the open-circuit voltage will change greatly, thus interfering with the delta-OCV self-discharge determination. It may take a day or more before the cell voltage is sufficiently stable.

The voltage measurement must be able to accurately measure millivolts in a measuring range of 4 to 5V. Most portable multimeters do not achieve this accuracy. By extending the waiting time between measurements, the voltage drop (and the SOC difference) will become greater and the difference will be easier to measure.

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[26] Seong, W. M., Park, K. Y., Lee, M. H., Moon, S., Oh, K., Park, H., Lee, S., & Kang, K. (2018). Abnormal self-discharge in lithium-ion batteries. Energy and Environmental Science, 11(4), 970–978. https://doi.org/10.1039/c8ee00186c

[27] https://www.electronicdesign.com/technologies/test-measurement/article/21808344/keysight-technologies-measure-selfdischarge-using-ocv-on-lithiumion-cells

Temperature also plays a role. Even small temperature differences induce a change in the open circuit voltage. This effect is all the more important if the waiting time between measurements becomes shorter, and the delta OCV is therefore smaller.

### 6.7.2 POTENTIOSTATIC APPROACH

Another way to determine the self-discharge is to keep the relaxed cell at a constant voltage and measure the current required for this. This requires a very accurate voltage measurement and a calibrated adjustable current source.

## 6.8 OTHER EXPERIMENTAL TECHNIQUES

A battery cell remains a very complex electrochemical system, of which we can only measure the voltage, current and temperature directly from the outside with conventional equipment. However, recent research also explores analysing the internal state by using acoustic waves. As described earlier, a lithium cell is made up of several alternating layers of electrodes, separators and electrolyte. Because the structure (including porosity) of these layers changes to different degrees when the cell is charged or discharged, a wave will behave differently depending on the SOC. The theory behind this is based on the reflection and transmission of waves in heterogeneous materials, especially in liquid-filled porous and solids (Biot's theory).

By using lower frequencies (order 100's and kHz) and cheap piezo transducers good information can already be obtained[28], but there are many obstacles to get at a robust and reliable method.

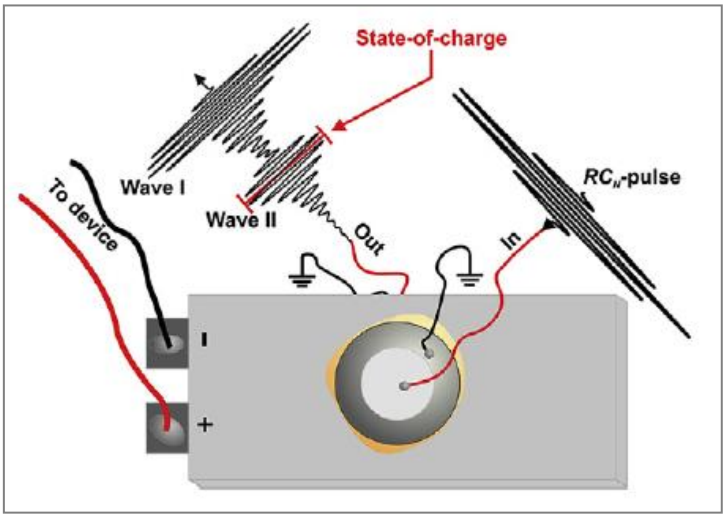

Figure 19: Acoustic method with piezo transducers at low frequencies [29]

One company that is exploring this commercially is Feasible.io[30] , with their EchoStat.

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[28] L. Gold, T. Bach, W. Virsik et al., “Probing lithium-ion batteries' state-of-charge using ultrasonic transmission – Concept and laboratory testing,” Journal of Power Sources, Volume 343, 2017, pp 536-544, http://dx.doi.org/10.1016/j.jpowsour.2017.01.090

[29] https://www.feasible.io/

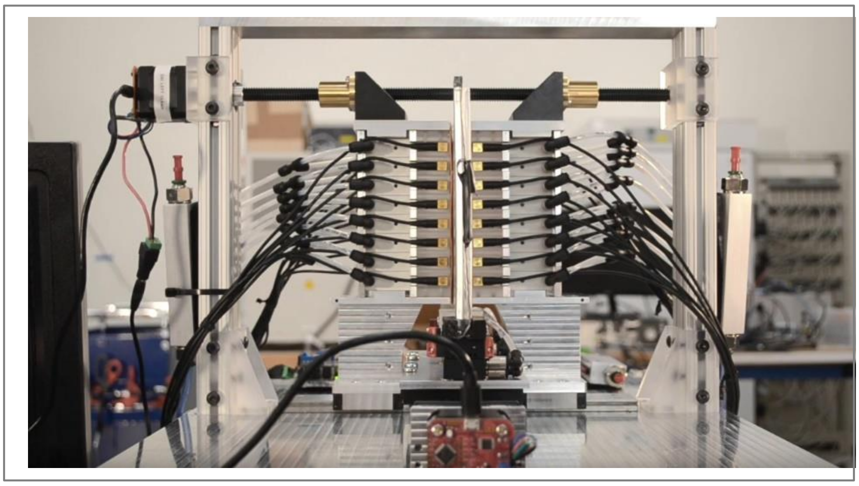

Figure 20: Test set-up for acoustic measurements from Feasible (footnote 29)

# 7. TECHNICAL ASPECTS OF BATTERY REPURPOSING

## 7.1 DIRECT REPURPOSING

In an optimistic scenario, the used battery can be mounted unchanged in the second-life application. This means that the industrial battery is connected to the new application without dismantling or modifications. Depending on the complexity of the battery, there are a number of challenges arising, concerning the battery's dimensions, weight, electrical connection, BMS communication and thermal management.

For all repurposing types, the necessary equipment to lift batteries is an important issue. It is generally overlooked how weight affects internal logistics flux. The machine used to lift a 150kg battery and a 715kg battery is not the same, and have different permits requirements. (R489 3 and 4 for example in France).

### 7.1.1 DIMENSIONS AND WEIGHT

The battery packs of EVs are quite heavy and large due to their large capacity and mechanical strength. In combination with their rather flat shape, direct repurposing is more likely to lead to larger static storage applications, where there is the option of stacking. If the battery pack is not completely flat but with bulging parts (see Figure 42 later on in this chapter), the empty space cannot be used in a repurposed application and the overall energy density becomes rather low.

| Type | Battery Weight |
|---|---|
| Nissan Leaf | 300 kg |
| Tesla Model 3 | 480 kg |
| Tesla Model S | 450 kg |
| Audi eTron | 715 kg |

Table 2: EV battery examples

### 7.1.2 ELECTRICAL CONNECTION

The second-life application of the battery used must have a voltage-current range similar to that of the original application. For today's EV batteries, the voltage is typically in the order of 350-400V, and 700-800V in the near future. Industrial batteries from applications with lower requirements and power (e.g. forklifts and AGVs) are more likely to be 48-96V.

Batteries of electric vehicles are often equipped with manufacturer-specific connectors and undergo extensive integration. For example, Tesla integrates the inverter, DC/DC converter and part of the fast charging system in the battery pack in its Model 3 (**Figure 21**). Deep integration increases efficiency and reduces production costs, but makes second-life use more complex.

Figure 21: Tesla Model 3 battery pack with extensive integration: e.g. HV interconnections, DC/DC converter and fast charging port.[31]

### 7.1.3 BMS COMMUNICATION

For safety reasons, battery packs from vehicles have dual high voltage contactors that interrupt both poles, along with a precharge circuit. These contactors are controlled by the BMS. The measurement of the battery current, individual cell voltages and temperatures, and the control of balancing circuits are also tasks of the BMS. The BMS is not separate from the rest of the vehicle and needs explicit commands to close contactors, send measured values or possibly activate thermal management.

The fact that every vehicle manufacturer implements its own closed BMS system and considers the communication with it as their intellectual property makes it difficult for remanufacturers to test or deploy battery packs in their entirety. As briefly mentioned above, without agreement with the original manufacturer, they have to rely on reverse engineering and unofficial third party solutions[32].

### 7.1.4 THERMAL MANAGEMENT

Most EVs use some form of thermal management to cool or warm the battery. Thermal management with coolant pumped in channels along the cells is most common, such as in the Tesla Model S and 3, and the Audi eTron. At Tesla, the cooling line runs between the individual cells, while at Audi the battery modules are in contact with a cooling plate along the bottom (**Figure 22**). Once out of the car, that functionality (pump, radiator…) must be provided externally to the pack.

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[31] https://electrek.co/2018/07/26/tesla-model-3-teardown-electric-powertrain/

[32] SimpBMS: https://www.secondlife-evbatteries.com/products/simp-bms

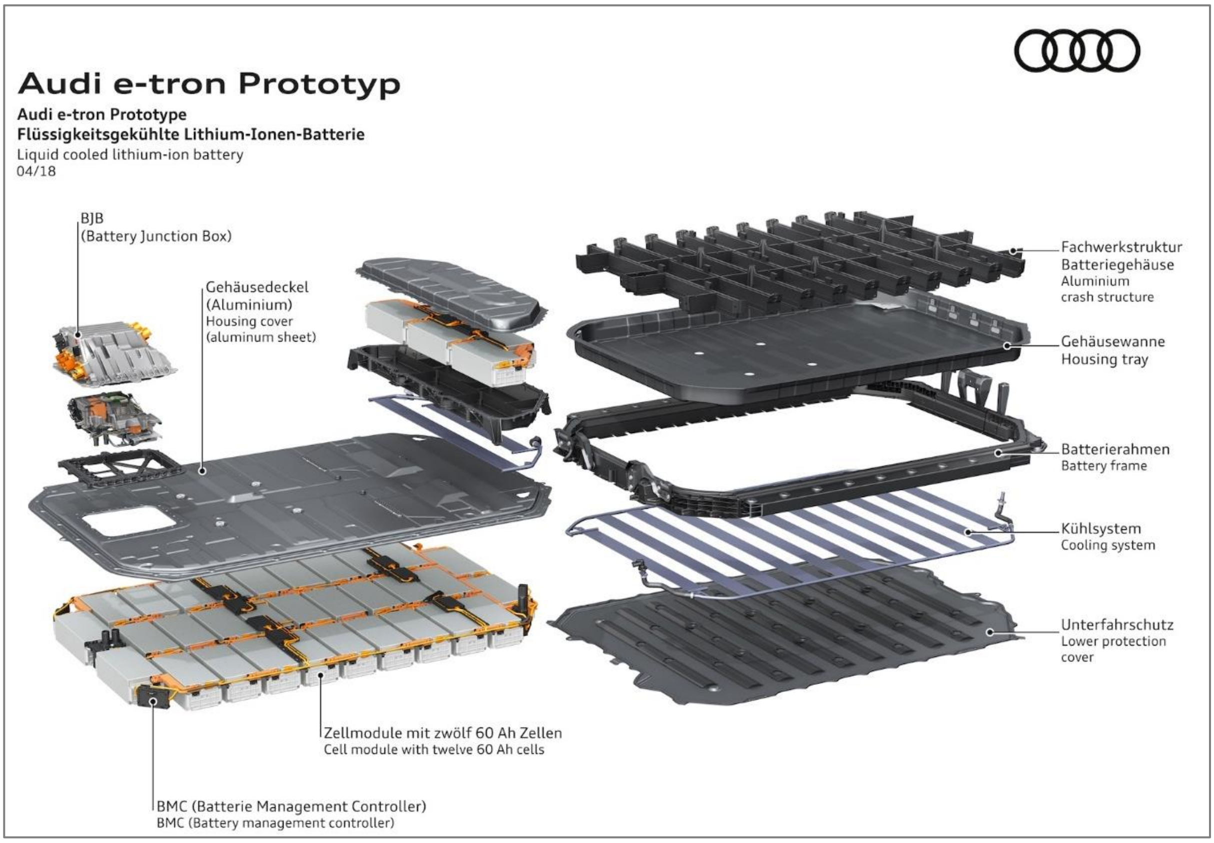

Figure 22: Liquid-cooled battery pack of the Audi eTron[33]

In a single case, the BMW i3, a heat pump is used in which the evaporator for the refrigerant gas is built into the bottom of the pack (**Figure 23**). In case of repurposing, the rest of the cooling circuit must also be built externally, including a compressor and condenser. Its implementation in a repurposing application does not seem economically feasible.

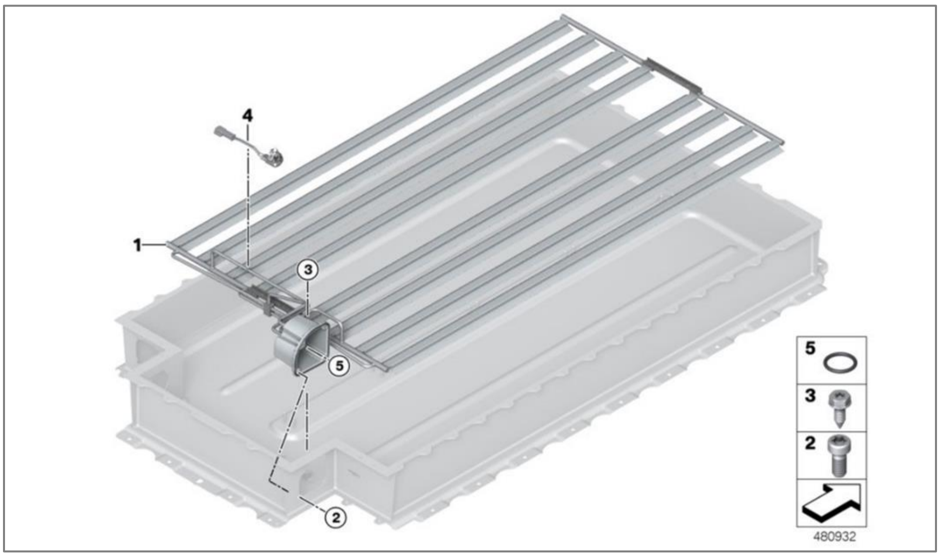

Figure 23: Evaporator for cooling the BMW i3 battery pack[34]

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[33] https://emobilitaetblog.de/audi-e-tron-weltpremiere-des-ersten-rein-elektrischen-serienmodells-der-marke/

[34] BMW i3 parts manual

However, before implementing such complex systems, the first point is to check whether cooling of the cells is necessary in the second-life application. The heat production is the result of high loading, which in a vehicle mainly occurs during hard acceleration and during fast charging. If the repurposing application can limit the power by, for example, distributing it over several batteries or by reacting dynamically to the current cell temperatures, it can be decided not to provide active cooling anymore. This trade-off must be made on the basis of the expected usage profile and a battery model whose parameters can in principle be derived from previous tests (in particular the internal resistance).

### 7.1.5 CONCLUSION

The direct repurposing of battery packs is very interesting because it makes it possible to put together large storage capacities cost-effectively, without the large investment costs of dismantling, performing separate cell or module tests and remanufacturing into a pack. Tests are still needed but at pack level and they are more easily done thanks to the facts that the "brains" are still attached to the "body". There is still a grey area concerning recertification for those batteries. But as long as nothing is changed and the battery is used within the same operating conditions, this should have an automatic green light.

The above challenges mean that direct repurposing of industrial and EV batteries is mainly reserved to the original manufacturers or companies who have an agreement with them, having access to all the necessary documentation, tools and software to carry out the repurposing process smoothly. This is illustrated, for example, by the BMW Speicherfarm Leipzig, mentioned in Annex B, where used batteries of the first generation BMW i3 are used in a stationary storage system. The repurposing manufacturers also indicate that the cooperation of the manufacturer is necessary.[35] The agreement must cover the use of IP and the responsibility share when the repurposed batteries are used.

## 7.2 DISMANTLING

In addition to direct repurposing, a battery pack can also be dismantled first. An EV battery is organized hierarchically: at the lowest level there are the individual cells, with internally a positive and negative electrode, separator, electrolyte and the cell housing. The cells are then grouped into modules by connecting them in series or parallel, which are again provided with a housing or mechanical attachment. The modules in turn are usually connected in series and housed in the battery pack housing together with sensors, contactors, BMS components.

### 7.2.1 CELL TYPES

Battery cells are produced in various sizes and shapes. The types available on the market can be divided into 3 groups: pouch, cylindrical or prismatic.

#### POUCH CELLS

A pouch cell, as the name suggests, is a hermetically sealed pouch containing a number of layers of copper and aluminium foil. The foils are provided with anode or cathode material, with a separator in between. Usually this structure is repeated several times, and then hermetically sealed in the typical silver-coloured pouch.

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[35] https://www.recyclingtoday.com/article/connected-energy-uk-elv-battery-recycling-repurposing/

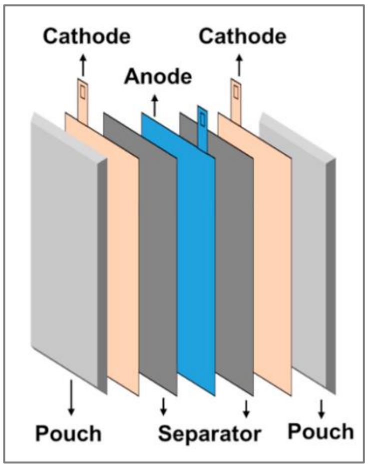

Figure 24: Pouch-cell construction

Figure 25: Kokam brand pouch cells

The advantage of pouch cells is that they can be made in many shapes and are quite light due to the lack of protective housing. In practice, pouch cells are therefore always packaged in a sturdier casing.

Gassing and volume change can occur in lithium batteries during charging and discharging, even if the cell is not mishandled. For pouch cells that are not mechanically clamped, that gas can lead to swollen pouches, as shown in **Figure 26**.

Figure 26: Swollen pouch-cell[36]

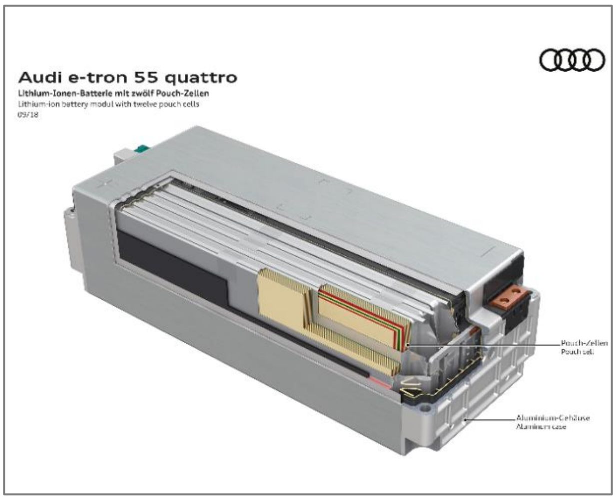

Figure 27: Audi eTron battery module with 12 pouch cells (source: Audi)

For example, the NMC cells in the modules of the Audi eTron battery are of the pouch type (**Figure 27**). There are twelve 60Ah pouch cells from LG in each module, connected as 4P3S or 4 in parallel three times in series.

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[36] https://batteryuniversity.com/learn/archive/pouch_cell_small_but_not_trouble_free

### CYLINDRICAL CELL

A cylindrical cell (**Figure 28**) is basically a rolled-up version of a simple pouch cell, also known as a 'jelly roll'. The roll is secured in an aluminium container, and the top and bottom of that cylindrical housing are then clamped. The lid also inclueds a pressure relief valve, in case there should be a strong gas pressure build-up in the cell.

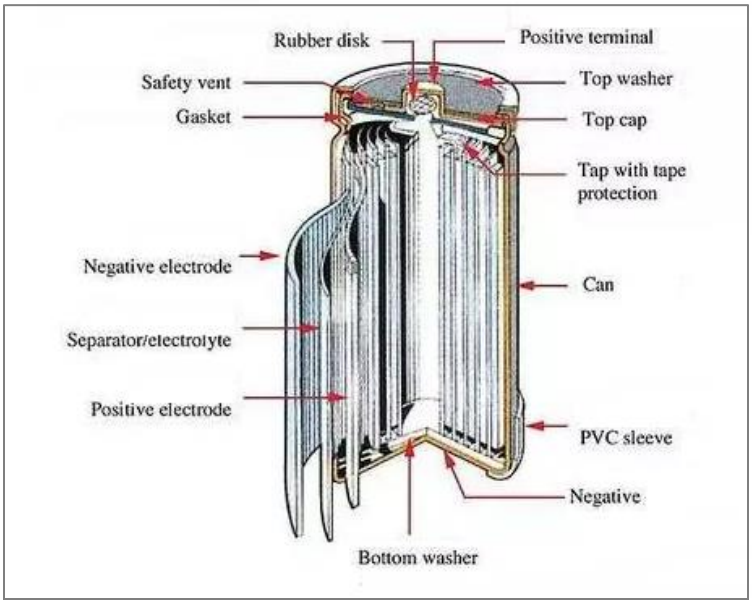

Figure 28: Construction of a cylindrical cell[37]

The most famous cylindrical housing is the so-called 18650 (18mm wide and 65mm high) and has its origins in the 1990s for use in portable electronics. Tesla is also known for the use of this format cell in the battery packs of its Roadster and Model S. The latter contains 7104 of these cells, divided over 16 modules. Due to energy density, this is evolving into larger sizes, such as the proprietary 21700 in the Model 3 and the announced 46800.

### PRISMATIC CELL

A prismatic cell is similar in structure to the pouch cell, but is constructed of more multiple layers and packaged in a rigid metal or plastic housing. Instead of stacked layers, it can also be rolled up around a wide centre piece. Prismatic cells are very popular in industrial applications and EVs, because they combine high capacity with an easily deployable shape. The downside, however, is a higher production cost and slightly poorer thermal behavior.
As an example, the BMW i3 uses prismatic Samsung-SDI cells, as shown in **Figure 29**.

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[37] https://medium.com/battery-lab/advantages-of-pouch-cell-battery-trend-and-opportunities-d08a5f0c6804

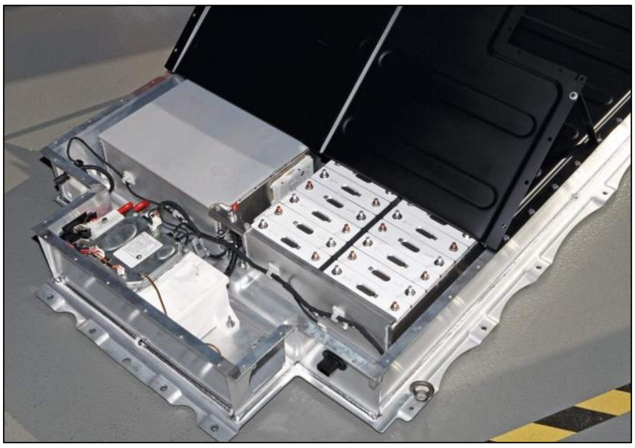

Figure 29: Prismatic cells in a BMW i3 battery pack[38]

### 7.2.2 BATTERY ENCLOSURE

The design of the battery housing logically follows from the requirements of the (original) application. The housing is intended to protect the cells and components of the pack, and sometimes functions as a structural element.

In electric vehicles we mainly find aluminium because of its weight, despite the higher cost. In certain applications, the extra weight of a steel housing is desirable, such as forklift trucks or electric pallet trucks[39]. There, the switch from lead-acid to lithium batteries may result in the intentional addition of ballast to the packs to ensure stability.

Figure 30: Battery packs for use in forklift trucks

Battery packs for vehicles used on public roads must also comply with the UN ECE R100 regulation[40]. In its second revision from 2013, this document contains a list of tests that must guarantee the safety of electric powertrains, including the battery, and have a strong impact on the design of a battery enclosure. The UN ECE R100 tests include the following aspects:

Vibrations and shocks: frequencies from 7 to 50Hz for 3 hours. Shocks of 28G and 15G, longitudinal and transverse respectively, mimic sudden deceleration and collision.

Thermal shocks: temperature evolutions between -40 and +60°C.

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[38] https://pushevs.com/2018/04/05/samsung-sdi-94-ah-battery-cell-full-specifications/

[39] https://batterysupplies.be/en/production/products/cyclic-batteries/lithium-ion/

[40] ECE R100 rev.2: https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2013/R100r2e.pdf

Mechanical impact: lateral pressure on the 10-ton pack.

Fire safety: exposure to a flame up to 700°C for 70s.

External short circuit, overcharge, over-discharge and overheat: to test the internal protection.

The requirements ensure that such battery packs are almost always made of ≥3mm aluminium with internal reinforcing ribs, and sometimes provided with thermal insulation inside.

### 7.2.3 JOINING TECHNIQUES

A crucial aspect in dismantling is the way in which modules and/or cells are attached to each other or to the conductors. This is of course strongly related to the type of cell, and requirements such as heat dissipation or electrical resistance[41].

MECHANICAL

The most ideal situation for repurposing or repair is when cells or modules are mechanically connected with screws and clamps. This is common at the module level, but it is applied to a lesser extent at the cell level, mostly on prismatic cells.

Figure 31: Cells with mechanical attachment (public sources)

The use of screws, nuts and connectors adds extra weight and labour to the manufacturing process, making it mainly used in industrial and EV batteries on larger groups of cells together (module and pack) or relatively small packs of large cells. For example, the Toyota Prius hybrid uses a mechanical assembly to connect the cells.

ULTRASONIC WELDING

Ultrasonic welding of metals (UMW) is widely used in battery assembly and can be used on a wide range of metals and metal foils. The surfaces to be connected are pressed by a so-called sonotrode. The latter briefly transmits ultrasonic vibrations (≥20 kHz) to the workpieces (**Figure 32**). The shear forces and plastic deformation this produces create a strong atomic bond.

The advantage is that this is a very fast and energy-efficient process that can connect different types of metals (e.g. aluminium on copper). However, as the vibrations can damage the internal connections in cylindrical or

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[41] Das, A.; Li, D.; Williams, D.; Greenwood, D. Joining Technologies for Automotive Battery Systems Manufacturing. World Electr. Veh. J. 2018, 9, 22. https://doi.org/10.3390/wevj9020022

prismatic cells, it is only suitable for use on the tabs of pouch cells. In the Chevrolet Volt battery pack, the battery tabs are connected to the busbar by means of an ultrasonic welding.

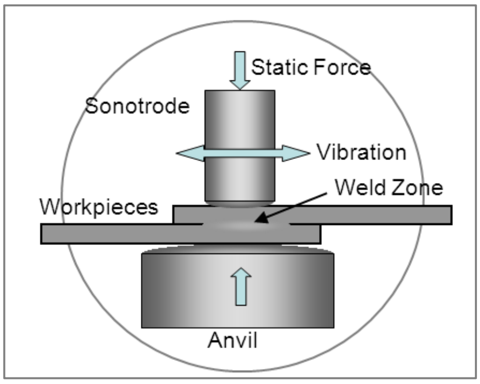

Figure 32: Ultrasonic welding process[42]

### SPOT WELDING

Spot welding is another commonly used technique for joining cells and uses the electrical resistance of the materials to be joined. When a high current is sent through, a strong warming occurs locally. Because a pressure is exerted simultaneously, the materials melt together.

Spot welding is applied when the two materials are not too thick (up to 0.4mm) and the weld should not be too large. Spot welding works on steel, nickel, copper and aluminium but is more difficult on the latter two due to their low electrical resistance and good thermal conductivity. The presence of oxides on the surface of aluminum also creates additional complications.

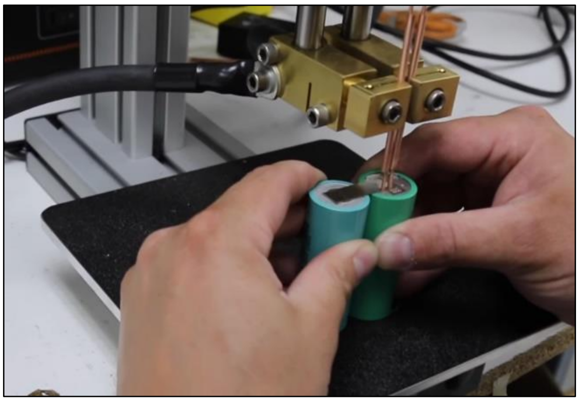

Figure 33: Manual spot welder[43]

### MICRO TIG

Micro-TIG or Pulsed Arc Welding (PAW) uses a scaled version of Tungsten Inert Gas (TIG) welding, but without adding the welding wire. An arc is only set up for a very short time (milliseconds) under a protective gas (Argon), so that the heat in the material remains limited. PAW is used for joining thin nickel, copper or steel strips[44]. This method does not appear to be widely applied in the production of EVs.

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[42] https://ewi.org/ultrasonic-metal-welding-for-lithium-ion-battery-cells-2/
[43] https://sunstonewelders.com/applications/battery/micro-welding-nickel-battery-tabs/
[44] https://www.amadaweldtech.eu/knowlegde-base/welding-conductive-battery-interconnects

Figure 34: Automated micro-TIG device

### ULTRASONIC WELDED JUMPER WIRES

The ultrasonic welding of wires (ultrasonic wire bonding) comes from the semiconductor industry, where it is used to connect so-called silicon 'dies' in chips. A thin aluminium, copper or gold wire, <500 µm, is pressed through a supply tube onto the surface to be joined. The wire is welded by ultrasonic vibrations. This process can connect different materials over small distances and the 'bond' wire can act as a fuse. Thanks to the many years of knowledge in the industry, it is a very fast and automated process.

Ultrasonic welding of bond wires is used, inter alia, by Tesla to connect 74 individual cells in parallel (**Figure 35**).

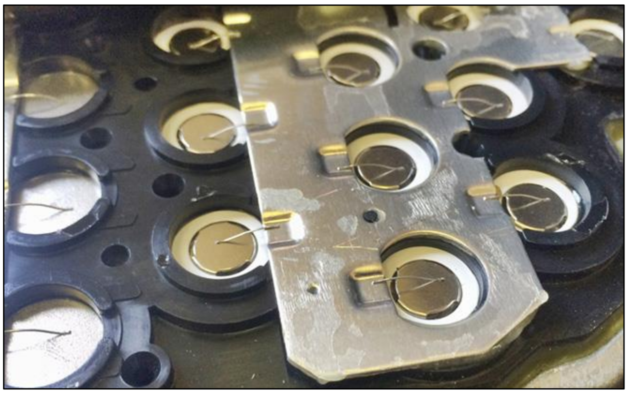

Figure 35: Ultrasonically Welded Wires on Cylindrical Cells[45]

### CLINCHING

With pouch cells, with a tab connection, it is possible to make a connection by simply pressing the metal foil against the conductor with a mould. This only works for thin structures, in the order of 0.2 to 4mm. The advantage is that riveting does not introduce heat and can hold different metals together. However, it is a fairly slow process and there is a chance that the clamp connection will come loose due to vibration or corrosion.

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[45] https://chargedevs.com/features/a-closer-look-at-wire-bonding/

### SOLDERING

Soldering directly to a cell is possible but not recommended. The heat required spreads quickly through the aluminium or copper conductors and can damage the cell, the seals or the pressure relief valve. The supply of heat into the cell must be absolutely avoided to avoid degradation or in the worst case thermal runaway. Soldering on aluminium is more difficult, but possible with aggressive fluxes. That is why direct soldering is hardly used, if at all, when connecting cells.

### LASER WELDING

In laser welding, a focused laser beam is used to very locally heat the parts to be joined. This technique makes it possible to make thin but deep welded connections at high speed. The speed also limits the heat input into the conductors. Laser welding is not only used at the cellular level, but also to put busbars and modules together, or to weld housings hermetically closed [46]. In the BMW i3, for example, laser welding was used for the cell connections in the modules (**Figure 37**).

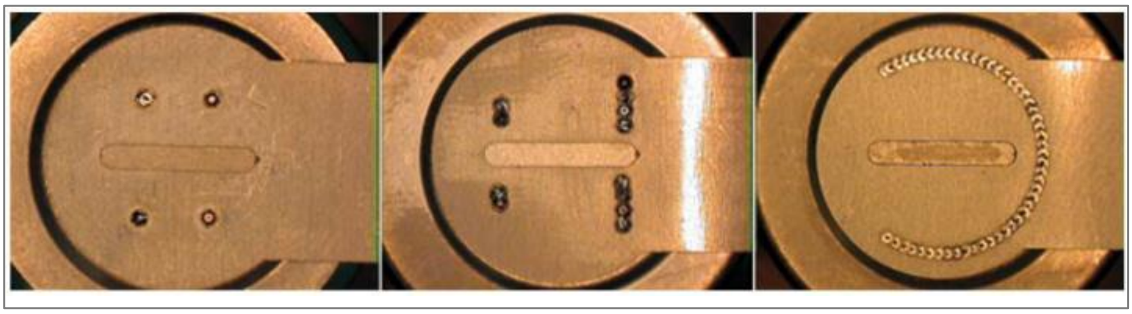

Figure 36: Connections between busbar and cylindrical cells using laser welding[47]

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[46] https://www.trumpf.com/nl_NL/oplossingen/sectoren/automotive/e-mobility/battery-packs-laserstraallassen-en-laserstraalreinigen/

[47] http://cii-resource.com/cet/fbc-05-04/Presentations/BMF/Cai_Wayne.pdf

Figure 37: BMW i3 laser welded cell connections[48] and battery pack

### 7.2.4 THERMAL INTERFACES AND MECHANICAL FIXATION

Good thermal management of battery packs is important when exposed to varying weather conditions (such as an EV), as well as during fast charging or power-intensive load profiles. This is not only about keeping the temperature of the cells within optimal limits, but also about keeping the temperature gradient in the pack as small as possible. If not, for example, the cells in the middle of a pack will heat up on average and degrade faster. This eventually manifests itself as increased self-discharge and internal resistance, and greater imbalance between the cells in the pack.

In order to limit the temperature gradients as much as possible, cells are cooled as directly as possible, which has a major impact on the mechanical attachment of modules and/or cells. In practice, therefore, modules are provided with cooling plates between cells. It is also possible to cool cells via the connections. This is because the heat spreads more easily along the current collectors of the electrodes than perpendicular to them. The heat therefore easily travels to the poles and then easily conducts further if the poles are connected via aluminum copper. An electrical protective foil and a cooling plate are then applied on top of this.

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[48] https://leandesign.com/bmwi3-videos-carbon-fiber-battery-pack-interior/

### COOLING CHANNELS

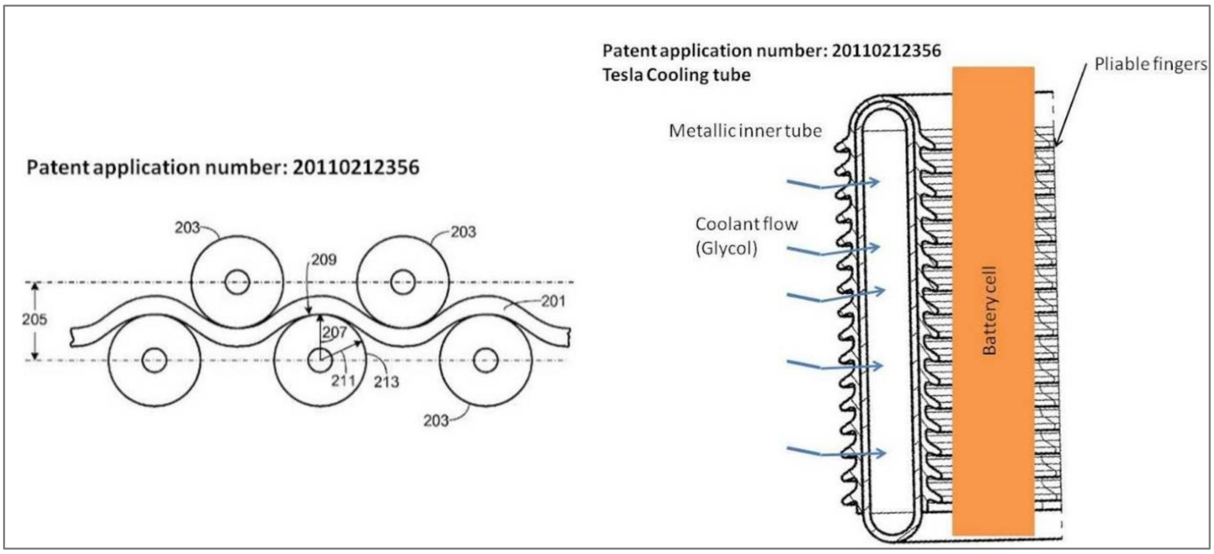

Figure 38: Tesla Model S cell cooling by means of flat tube and thermally conductive fingers[49]

For example, in the Tesla model S pack, the 18650-sized cells are glued into the modules, with an aluminium cooling channel winding between them. All 16 modules are connected in series, and the water-glycol mixture passing through them is cooled by a heat pump. A thermally conductive material has been applied to the channel (so-called gap fillers and conductive pads, which are typically used in the electronics industry for cooling semiconductors).

With the Tesla Model 3, the entire space between cells in a module is filled with gap filler, which makes disassembly practically impossible (**Figure 39**).

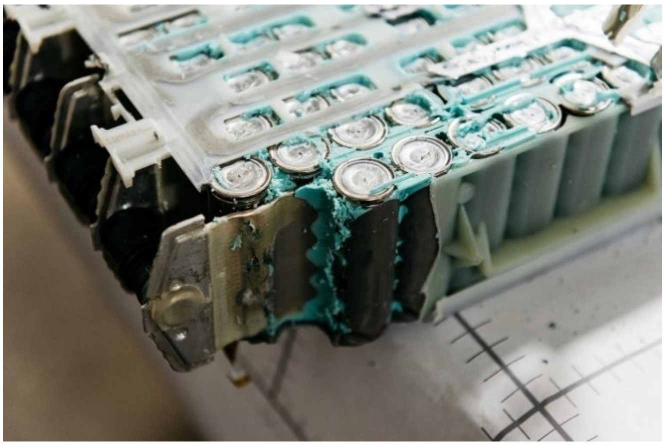

Figure 39: Tesla Model 3 cells with cooling channel and gap filler[50]

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[49] https://patents.google.com/patent/US20110212356A1/en

[50] https://teslaownersonline.com/media/tesla-model-3-teardown-9.677/

### COOLING PLATE

Another way to cool cells is to fix them at 1 or 2 sides on, or partly in, a cooling plate (with electrically insulating but thermally conductive material). As a result, the distance between the cells can be made smaller than when cooling channels are used.

This principle is used in the Audi eTron, for example. The horizontal cooling plate at the bottom of the pack cools the modules (**Figure 22**), which internally have vertical cooling plates between the pouch cells (**Figure 27**). A mixture of water and glycol runs through the horizontal cooling plate, which in turn can be cooled by means of a heat sink. The BMW i3 skips a step and immediately uses a heat pump to cool the cooling plate (functioning as an evaporator for the refrigerant gas) (**Figure 40**).

Figure 40: Evaporator/cooling plate at the bottom of a BMW i3 battery pack (public source)

### AIR COOLING

If the heat production during load and (fast) charging remains limited, consideration can be given to omitting the complexity of a cooling system with liquid or gas. The cells are then cooled passively (by conduction and convection) or actively (by means of a fan or blower). The battery pack in the Toyota Prius (**Figure 41**) features a blower that pops up when the temperature rises, while the pack in the Nissan Leaf relies on fully passive cooling.

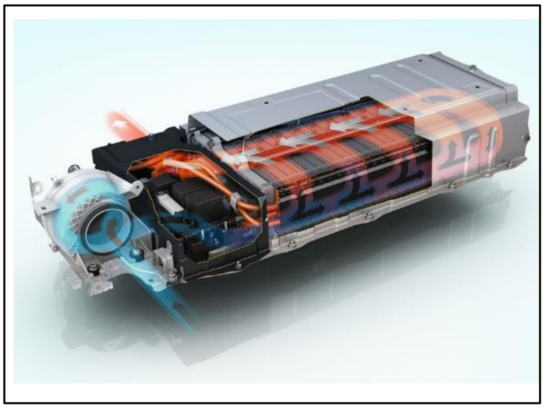

Figure 41: Toyota Prius . Active Air-Cooled Battery Pack (public source)

Figure 42: Nissan Leaf . passive air-cooled battery pack (public source)

### 7.2.5 CONCLUSION

The previous sections discussed the methods used to assemble batteries on an industrial scale. This provides a good insight into the challenges required to go the opposite way: decommissioning.

The construction methods (in terms of cooling and cell connections) generally make it very difficult or impossible to remove individual cells from a module for repurposing, let alone to do so cost-effectively. However, intact recovery of the (larger) modules is feasible, if one can be satisfied with abandoning the original BMS system. In practical terms, its use is only an option if the entire pack is immediately reused.

In the field of EV batteries, the trend seems to be towards far-reaching integration of the battery pack with other systems. This was already illustrated by the Tesla Model 3 (**Figure 21**), where the DC/DC converter and fast charging hardware were integrated into the pack. Tesla also plans to make the battery pack part of the car's supporting structure (a so-called Structural Battery[51]), in order to save weight and space. Such developments do not contribute to promoting the possibility of dismantling and reusability.

## 7.3 ASSEMBLY INTO A NEW BATTERY PACK

Logically, when cells or modules are deployed in a second-life application, the specifications of that resulting battery will be relatively lower than when used in the original application. The new specifications must follow from a careful assessment after the completion of the tests.

Finally, the assembly of the new pack will depend on the requirements of the new application. Given the ever-decreasing cost of (new) batteries, a certain balance has to be found in those requirements with the cost-effectiveness of repurposing. A newly assembled pack will also need a new BMS, new wiring (for the battery power but also the signalling), contactors, fuse(s) etc… The cost of all that, together with the required (mainly manual) connection and construction time, can quickly overshadow the acquisition cost of the cells. Exact figures can only be given in the context of a concrete application.

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[51] https://chargedevs.com/newswire/a-sneak-peek-at-teslas-new-structural-battery-pack/

## 8. PROPOSED ASSESSMENT PROCEDURE

The critical analysis of the UL1974 standard presented above was the starting point for designing a flow chart dealing with how to handle a battery intended for second life use, and to reach a more detailed description of the different required steps and procedures.

This standard contains a large number of conditions (e.g. use of the 'expiry date') and the entire procedure is labour- and test-time-intensive. Furthermore, the choice of selection and assessment criteria is left entirely to the repurposing manufacturer, as they have the best view of the requirements of the second life application and the reference values of 'new' cells or modules.

In this proposed test procedure, the repurposing of the batteries is divided into two parts: a preliminary stage in which quantitative selection criteria are drawn up and where it is checked whether cooperation from the original battery manufacturer is possible. This preparatory stage provides the basis for making the necessary choices in the actual repurposing process. To this end, an alternative flowchart to UL1974 is proposed that can be used as a guideline when selecting incoming batteries. The underlying idea is to carry out time-consuming tests as much as possible only to the point where most 'bad' batteries have already been removed. Given the time, risks and costs associated with dismantling and reassembling batteries into new packs, direct repurposing is preferred. This means that the battery is used in its entirety in the new application.

The preliminary stage is shown in **Figure 43**. It is a “close-up” of the aspects and considerations that can be discussed in the preliminary stage. Where relevant, reference is made to sections of this report.

**Figure 44** shows the course of the test procedure within the repurposing process. Depending on the second life requirements and predefined limits with regard to cost and time, it is possible to choose to skip part of the assessment tests (indicated by dotted lines). After the reassembly, a 2nd life pack must be subjected in its entirety to validation tests, so it can sometimes make sense not to test the dismantled modules or cells individually first and thus save testing time.

The following paragraphs will discuss the preliminary phase and the proposed repurposing process.

### 8.1 PREPARATORY STAGE

Each repurposing process preferably starts with making agreements with the original manufacturer. When documentation and/or tools are available, battery assessment can start with:

Reading out of the BMS. With that, the repurposing manufacturer immediately knows the voltages of the individual cells and possible cause of the pack write-off in the original application. Bad modules can thus be identified before the pack is opened.

Measured values are compared with reference values for the purpose of the selection criteria.

Upgrade of the BMS to suit the new application. This can involve the limit of a overcurrent protection by software, but also physical elements such as fuses must be adapted or replaced by relevant equivalents.

Possible dismantling will be faster through insight into the procedures of the original manufacturer.

The collected batteries have different quality, since they might have possible damage and also depending on battery parameters such as the actual capacity. That is why, in the preliminary phase, consideration must be given to whether various applications for a second life are possible, so that a larger part of the supply can be reused. The cell level measurement plan described in Appendix C of UL 1974 helps to find out how long the batteries can last in the intended applications. It is probably not possible to wait for this plan to be completed before going to the market because the limiting ageing can take several years, as is also desired in the new application. It does, however, provide substantiation that the selected applications are in order and an application may have to be waived for a certain type of battery after the measurement plan has been completed. This is also referred to in the quality assurance.

Within an application, batteries can be further classified according to quality, such as the actual capacity: if separate parts of battery packs (usually modules) are combined, it is important to combine equivalent modules. At the pack level, this is usually less important because each pack is connected to an inverter and thus they can operate independently of each other. Classification based on quality criteria is called binning.

In the preliminary phase, the reference values for the (internal) selection criteria are determined for each intended application on the basis of the datasheet values for the first use, consultation with the original manufacturer and from the measurement plan. The distribution of the 'bins' is also determined in order to combine equivalent battery parts (modules) with each other. In this respect, the following criteria can be used:

maximum and minimum open circuit voltage

maximum allowed internal resistance

lower limit for capacity

maximum permissible spread of the open circuit voltage between cells in a module or over the entire pack

maximum allowed spread of the internal resistance

maximum deviation from the open circuit voltage for sorting dismantled modules or cells in the same group coming from the above whole pack

Insulation resistance between the battery terminals and the housing

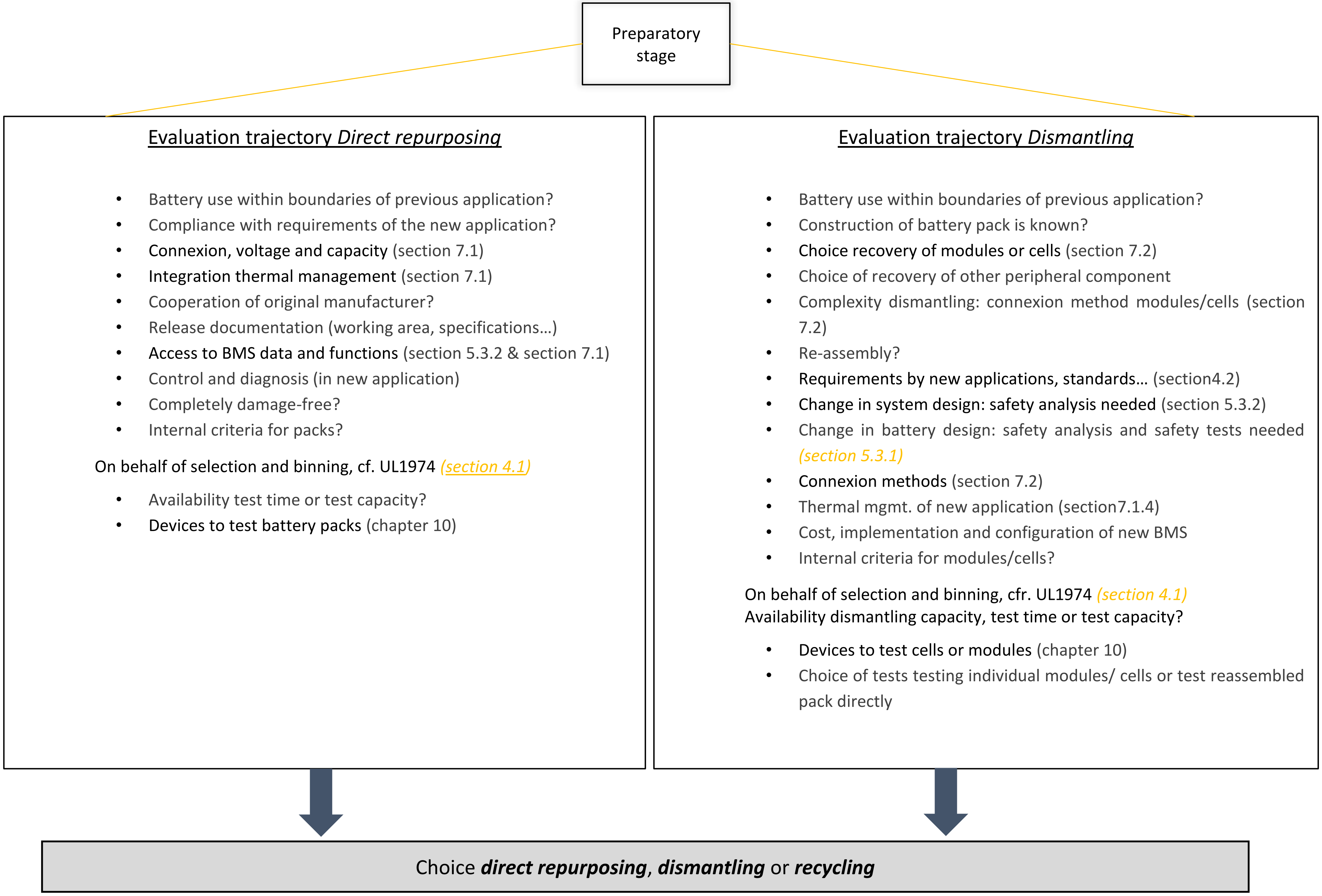
**Table 3** shows as an example of how the bins can be formed.

| **Criteria** | | | **Bin** | |
|---|---|---|---|---|
| Actual capacity | Internal resistance | Spread in OCV | Application | Quality |
| 95-90% | 100-120% | 0-5 mV | A | 1 |
| 90-85% | 120-150% | 5-10 mV | A | 2 |
| 85-80% | 150-200% | 10-15 mV | B | 1 |
| 80-75% | ,, | ,, | B | 2 |
| 75-70% | ,, | ,, | B | 3 |
| <70% | > 200% | > 15 mV | Recycling | – |

Table 3: Example from sorting method to application and quality. The worst feature determines the category: a battery with 92% capacity and 130% resistance ends up in bin A2.

In **Figure 43**, the considerations and challenges are once again presented as part of the preliminary process. Because the repurposing of the battery pack is technically preferred as a whole due to a minimal dismantling effort, this has been indicated as a separate route. The pack must then be completely damage-free and all parts must be within the specified reference values and also be sufficiently homogeneous. This leads to the internal criteria for the packs.

Now the repurposing process begins as depicted in **Figure 44**. Each step is run through in the next section.



Preparatory stage

Evaluation trajectory *Direct repurposing*

- Battery use within boundaries of previous application?
- Compliance with requirements of the new application?
- Connexion, voltage and capacity (section 7.1)
- Integration thermal management (section 7.1)
- Cooperation of original manufacturer?
- Release documentation (working area, specifications…)
- Access to BMS data and functions (section 5.3.2 & section 7.1)
- Control and diagnosis (in new application)
- Completely damage-free?
- Internal criteria for packs?

On behalf of selection and binning, cf. UL1974 *(section 4.1)*

- Availability test time or test capacity?
- Devices to test battery packs (chapter 10)

Evaluation trajectory *Dismantling*

- Battery use within boundaries of previous application?
- Construction of battery pack is known?
- Choice recovery of modules or cells (section 7.2)
- Choice of recovery of other peripheral component
- Complexity dismantling: connexion method modules/cells (section 7.2)
- Re-assembly?
- Requirements by new applications, standards… (section4.2)
- Change in system design: safety analysis needed (section 5.3.2)
- Change in battery design: safety analysis and safety tests needed *(section 5.3.1)*
- Connexion methods (section 7.2)
- Thermal mgmt. of new application (section7.1.4)
- Cost, implementation and configuration of new BMS
- Internal criteria for modules/cells?

On behalf of selection and binning, cfr. UL1974 *(section 4.1)*
Availability dismantling capacity, test time or test capacity?

- Devices to test cells or modules (chapter 10)
- Choice of tests testing individual modules/ cells or test reassembled pack directly

Choice ***direct repurposing***, ***dismantling*** or ***recycling***

Figure 43: Close-up of the preliminary phase, with important decision criteria

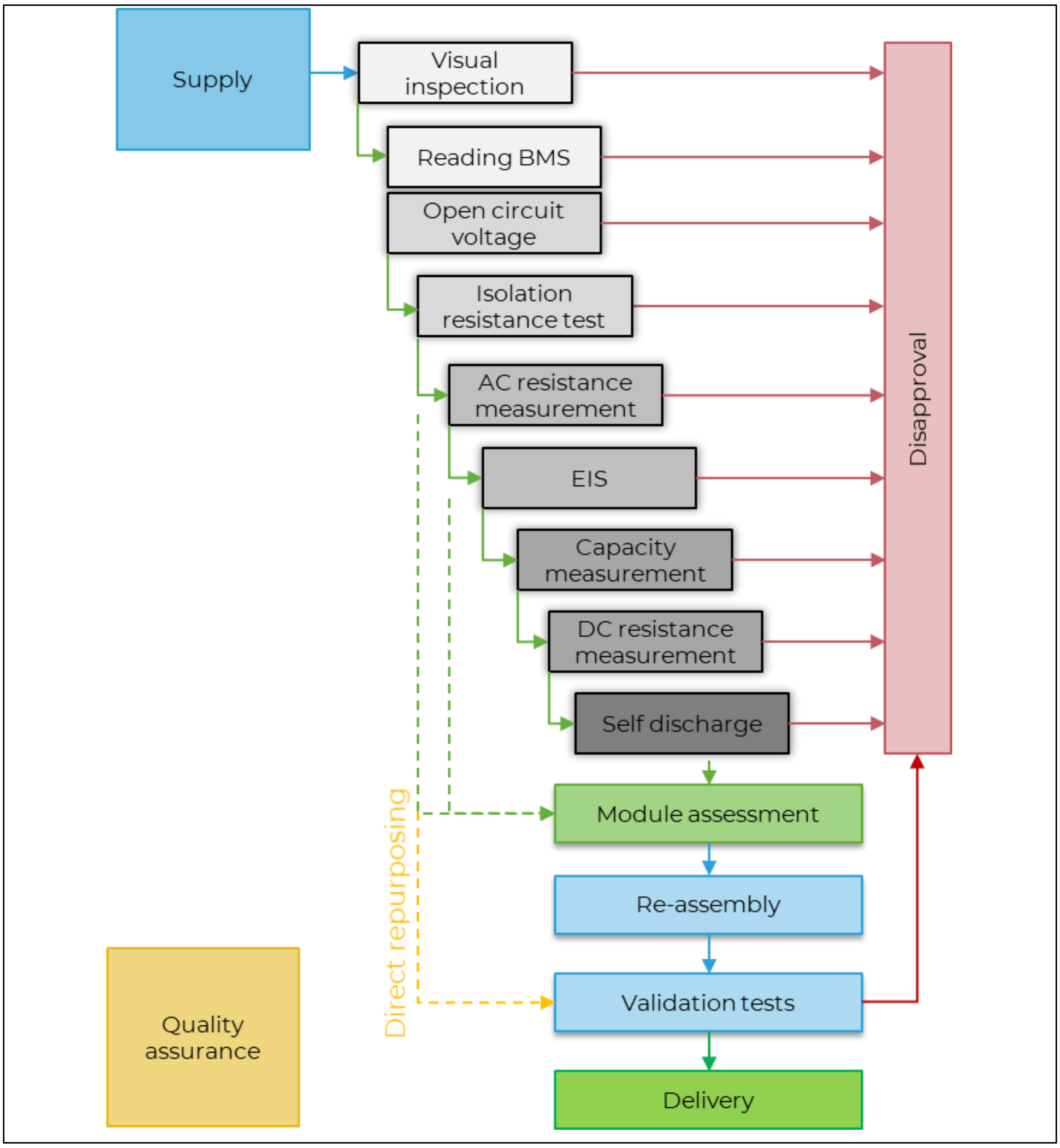


Figure 44: Course of the repurposing process

## 8.2 TECHNICAL PROCEDURE

### 8.2.1 VISUAL INSPECTION

As with UL1974, one of the first selection criteria is a visual inspection. The pack is checked for traces of fire, crash damage, transport or fall damage. This is a relatively short procedure. Rejected packs can either be written off completely or set aside for further disassembly and recovery, depending on the severity of the identified damage. Approved packs continue to the next step.

### 8.2.2 READING OF BMS DATA

After the first selection, it is possible to check in detail whether the package is still in good condition internally. The fastest way to do this is to read the data from the BMS. This provides information about the package as a whole and about the components in it. Both are important to evaluate possible repurposing. At a minimum, the BMS provides the following information:

- The amount of energy or charge that the packet has delivered (energy throughput)
- Module and/or cell voltage (open-circuit voltage) and its spread
- Correctness of temperature info (which if not can indicate damage)

If available, the following information can preferably also be read:

- The result of the BMS self-diagnosis
- The current capacity of the package
- Internal resistance of the package
- Internal (DC) resistance of the cells (or modules) and its distribution
- History of the balancing actions on the cells
- Condition of the contactor and/or fuse
- Critical events (over-temperature, overvoltage, …)
- Summary of usage history (e.g. by counters on hours of usage or total energy transferred)
- The peak load that the pack can deliver
- History of excessive shock and vibration
- Error history concerns BMS communication with the application side

In case of problems, it can also be determined which module or cell is responsible. The rejection of cells and modules will have to take place on the basis of the criteria and limit values drawn up by the repurposing manufacturer (minimum, maximum voltage, resistance and its spread) during the preliminary phase. If there is data about the usage history, this can play an important role in the selection.

The possibility of reading this data depends on the cooperation of the manufacturer during the preliminary phase. The future European Battery Regulation (see below) provides that manufacturers are obliged to make such data available. If not, the repurposing manufacturer is dependent on reverse engineering the electrical interface or the data protocol.

### 8.2.3 OPEN CIRCUIT VOLTAGE

If the BMS cannot be read out, then the battery pack, module and cell voltages must be measured manually. In most situations, the pack will have to be opened for this, because the pack voltage is shielded from the outside world by means of contactors, fuses or safety cut-outs.

Even if reading via the BMS is possible, it is recommended to check the reported values by direct measurement.

### 8.2.4 INSULATION RESISTANCE

Now that it has been found that the battery is undamaged and has sufficient voltage to be used, it must be checked whether the insulation resistance is still sufficient. This is a simple test that shows that there is no internal damage that could lead to a shock. This is described in section 0. If the battery pack contains its own insulation fault monitoring, it must first be disconnected, otherwise that resistance will be measured as a parallel resistance, which means that the minimum resistance according to the test will probably not be reached.

### 8.2.5 AC RESISTANCE MEASUREMENT

The AC resistance measurement can be performed quickly just like the previous measurement, and was previously described in section 6.5 and also in 0. This can be done at module level as well as at cell level if there is access to the cells. This will likely require different measuring devices as module voltage and cell voltage may be too far apart for one AC resistance tester.

### 8.2.6 IMPEDANCE MEASUREMENT AT MODULE LEVEL

Performing an EIS also provides information very quickly, and is an extension of an AC resistance measurement. However, the equipment is more expensive, and implementation at module level is more difficult (because of the higher voltages). The measurement technique was previously described in 6.6, and more practical information about the equipment can be found in 0. Access to the cells is required for this.

### 8.2.7 CAPACITY MEASUREMENT

Because a complete capacity measurement takes some time, it is only included in the test procedure at a late stage. For that purpose, the pack first needs to be fully charged, then discharged under controlled conditions, preferably in the nominal conditions defined in the pack's datasheet when it is available. If it is not, it is required to know the cells' chemistry in order to adapt the test conditions, in particular the maximum and minimum acceptable voltage and temperature. The charge/discharge rate should be chosen according to the intended application and the limitations of thermal management during the test. Typical test conditions are a temperature of 25°C and a discharge rate of C/2 (full discharge in 2 hours). Then, if the BMS communication protocol is unknown, the pack design must enable direct connection to the battery terminals, as illustrated on the picture below.

Figure 45 – Battery modules taken out of the pack’s casing with direct measurement of cells’ voltages

However, even if this setup enables capacity measurement, it will only be possible to perform a few cycles, but long-term operation will not be possible without a balancing system, to limit the difference between cells’ voltages. This means that a new BMS must be implemented before going on with the battery’s second life.

### 8.2.8 DC RESISTANCE MEASUREMENT

When there is the possibility to charge and discharge, a DC resistance measurement can also easily be performed since it uses the same test device. As indicated in section 6.5, this can be done in many ways, but the essence is that the conditions, method and results must be reproducible. Therefore it makes sense to do this test after the capacity measurement, since the SOC can be brought to a known value at the end of the capacity test.

### 8.2.9 SELF-DISCHARGE

Measuring self-discharge is a delicate process that requires time and a controlled environment. Its measurement can optionally be carried out when the cell or modules are already stored, assuming that the environmental conditions allow a good comparison afterwards. See section 6.7 for the two existing measurement methods.

### 8.2.10 RE-ASSEMBLY

After the quality inspection, the conversion to repurposing starts. If packages are dismantled into modules, those with the same properties (actual capacity and resistance) are of course taken together. If several modules are combined, they must be brought into the same state of charge (SOC) if they are connected to each other. This is “automatically” the case if the capacity test has taken place before. This is necessary because the voltage of all parts must be the same, otherwise strong equalizing currents may arise.

### 8.2.11 VALIDATION

Validation testing takes place at the end. This contains the tests that standards prescribe for the respective application. The minimum amount of tests are:

Recheck the open circuit voltage of the package, modules and cells. These had all been brought into the same condition during the assembling activity.

Insulation resistance test: test to ensure that no battery voltage is applied to metal parts of the housing. This monitors the production quality.

AC resistance measurement of the pack demonstrating the correct electrical conductivity of the connection of the components.

A test on the functioning of the BMS. This includes self-diagnosis, communication and a test of the safety functions.

A full discharge & charge cycle under relevant conditions of use showing that the recycled battery is working properly in the new application. If no capacity test has taken place in the battery evaluation test procedure, this test now provides a definitive answer about the remaining capacity and can therefore lead to rejection.

# 9. CONCLUSION

From an economic and safety perspective, direct repurposing is a lot more attractive than going through disassembly, but it requires access to the BMS, documentation on the control of the internal systems and ultimately cooperation from the original manufacturer. This is a tricky point, because many manufacturers see in repurposing competition or loss of control and therefore try to avoid or ignore repurposing. The new upcoming battery regulation aims to provide an answer to this by requiring documentation to be made available. Regardless of whether this initiative is successful, it is advisable to make agreements in advance with the manufacturer for each repurposing process.

Re-use through dismantling is more complicated, and will focus on recovering good modules from the pack. Detaching individual cells is practically only feasible if they are mechanically assembled, which is rarely the case. The choice is ultimately driven by the new application and the cost.

In order to select the batteries and modules efficiently and cost-effectively, we proposed, inspired by the UL1974, a test procedure that tries to quickly filter bad ones from the influx. Emphasis is put on the preparatory stage that is needed on the one hand to identify several possible applications for the incoming batteries and at the other hand to determine quantitative quality criteria.

Because the newly built battery must also be validated as a whole, the repurposing manufacturer will have to consider whether to test longer, or to build the new battery and validate it in its entirety. This decision should be based on samples and historical data, if available, which is part of the proposed quality assurance.

# 10. ANNEX A - COMMERCIAL MEASUREMENT DEVICES

This section examines which test equipment can be used to measure or determine the previously explained parameters. It is not an exhaustive list of commercially available devices, but only aims to give an idea of the possibilities.

## A.1 CAPACITY MEASUREMENT

For capacity measurements, battery testers exist that can charge and discharge batteries. These differ in voltage and current range. Multiple test channels are often offered in one device. Well-known brands include:

- PEC (BE)
- Digatron (DE)
- Basytec (DE)
- Maccor (US)
- Arbin (US)
- Chroma (TW)

Another method is to work with adjustable DC power supplies and DC loads. A variant of this is working with bidirectional DC power supplies. With these, their load power (which causes battery discharge) is usually a fraction of the power supply (which leads to battery charge). These solutions are more complex to use than a battery tester. This is because interaction with the battery communication usually has to be provided and additional data acquisition is required. The latter can be realized with a multi-channel digital multimeter. This then stores voltage and current over time, after which capacity and energy can be calculated. Known bidirectional power supplies exist at:

- Delta Electronika (NL)
- Itech (TW)
- Elektroautomatik (DE)
- Regatron (US)
- Toellner (DE)

Systems with inverters are suitable for large powers and high voltages. They have one channel per setup. This may be necessary for testing complete EV packages. Providers are for example:

- PEC (BE)
- Gustav Klein (DE)
- Heinzinger (DE)
- Berghof (DE)

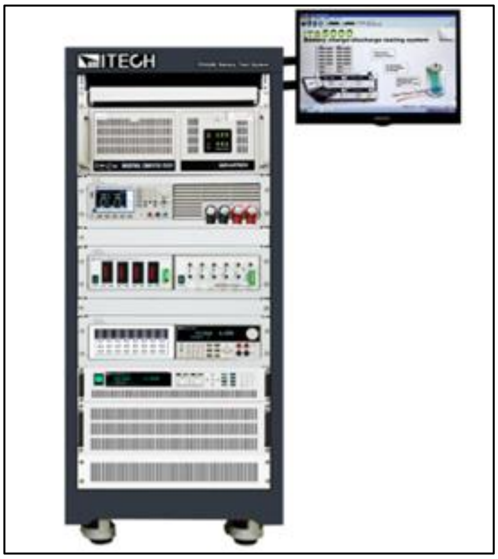


Figure 46: A bi-directional power supply and separate data acquisition units assembled in a mobile arrangement[52]

## A.2 INTERNAL RESISTANCE

Determining the internal resistance can be done by applying a current pulse to the battery or cell, and measuring the voltage change. However, this can be performed and interpreted in many ways, which was explained earlier in section 6.5.

Measuring the internal resistance thus requires a way to apply a controlled current step, and measure the resulting voltage at a reproducible time interval. The same battery test equipment as mentioned above is usually used for the pulse current method.

Note that many measuring devices called battery testers are intended for lead-acid batteries. They are useless for lithium batteries!

AC measurements at 1 kHz are standard devices, used in many electronics fields. There are special versions for batteries. The product range is then focused on multiple voltage ranges to go from cell, via module to package level. They can have multiple channels and are then used in the control phase of battery production lines. There are also hand-held solutions.

The following brands offer a wide range of 1 kHz measuring devices:

- Hioki
- Keysight
- Cadex (the company behind BatteryUniversity.com)

Sometimes the frequency can also be selected at a different point.

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[52] https://www.itech.sh/en/product/test-system/ITS5300.html

Figure 47: An AC resistance meter for EV battery packs in production environment.[53]

## A.3 ELECTROCHEMICAL IMPEDANCE

Electrochemical impedance measurement is performed at the cell level. Some battery tester manufacturers have built in such a meter and it can then be automatically connected to a channel. This is at least the case with Digatron and Gustav Klein.

There are many suppliers of impedance meters. However, many impedance meters are intended for analysing communication devices and therefore operate on batteries with the wrong bandwidth and/or at too high frequencies. Electrochemical must therefore be stated. They must be suitable for lithium batteries and with a frequency range between at least 10 mHz and 5 kHz. The signal output due to the imposed sine wave current must provide at least 5 mV. If the battery cell has a resistance of around 1 mΩ, the device must therefore be able to withstand 5 A. This significantly reduces the number of usable devices on the market.

Common brands are:

- Biologic (F)
- Metrohm Autolab (NL)
- Solartron (UK)
- PAR (US)
- Gamry (US)

Figure 48: Biologic MPG205 impedance measuring device

For module-level EIS measurements, measuring the response of individual cells, there is no ready-made measuring equipment. This can be built on the basis of a 4-quadrant power supply in combination with fast data acquisition equipment. With the latter it is important that it can withstand the total battery voltage. The channel-

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[53] https://www.hioki.com/en/products/detail/?product_key=6463

to-ground voltage must therefore be at least the battery voltage. Another solution is to use signal converters between the measurement and the measurement device or probes that separate the signal. VITO has developed its own setup for this.

Manufacturers of 4-quadrant power supplies, also known as bipolar power supplies:

- Toellner (DE)
- AE Techron (US)
- NF (US)

## A.4 SELF-DISCHARGE

The methods to measure self-discharge were previously described in section 6.7. A good measurement accuracy and test environment is essential to obtain meaningful results. The delta-OCV test method itself can be performed with a variety of commercially available DMMs, but 6.5 digit or higher accuracy will be required.

Figure 49: Fluke 8845A and Yokogawa DM7560 6.5 digit multimeter[54]

The potentiostatic method is more complex because of the required stable voltage source and current measurement. It is possible to build a test setup from individual commercially available devices. Keysight also provides an integrated solution with the BT2152.

Figure 50: Keysight BT2191A (left) and BT2152A (right) test setup[55]

In view of the sensitivity of the open-circuit voltage to external influences, determining the self-discharge can take a long time. With the potentiostatic measurement, the measurement time can be relatively short (12-24h), assuming that the cell is completely relaxed and its internal temperature is stable. For the delta-OCV method, 1 to 2 weeks must be allowed quickly.

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[54] https://www.fluke.com/en-us/product/precision-measurement/bench-instruments/fluke-8845a-8846a

[55] https://www.keysight.com/en/pc-2808110/self-discharge-measurement-solutions

## A.5 INSULATION RESISTANCE

The insulation resistance can be easily measured with hand-held equipment. This test is often also named after one of the measuring equipment manufacturers: Megger.

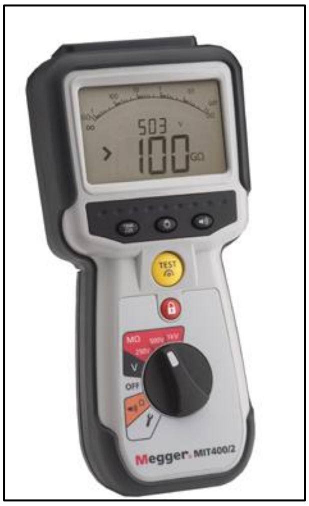

Figure 51: Insulation value measuring device[56]

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[56] https://megger.com/cat-iv-insulation-testers-mit400/2-series

# 11. ANNEX B - EXAMPLES OF BATTERY REPURPOSING

## INTRODUCTION

Batteries from some applications are not yet fully depreciated after their useful life in the initial application (which can also be a second-hand life). This mainly concerns traction batteries from hybrid or fully electric vehicles, such as passenger cars, buses and trucks, but also forklift trucks or excavators. The estimated growth is shown in **Figure 52**.

It is possible to deploy these batteries in applications with lower requirements, such as stationary storage. Vehicle manufacturers specify a capacity loss where the battery is considered depreciated (Renault: 70% remaining, VW: 80% remaining), because the driving range has decreased too far. However, for stationary storage this is less relevant as there is usually enough space available to compensate.

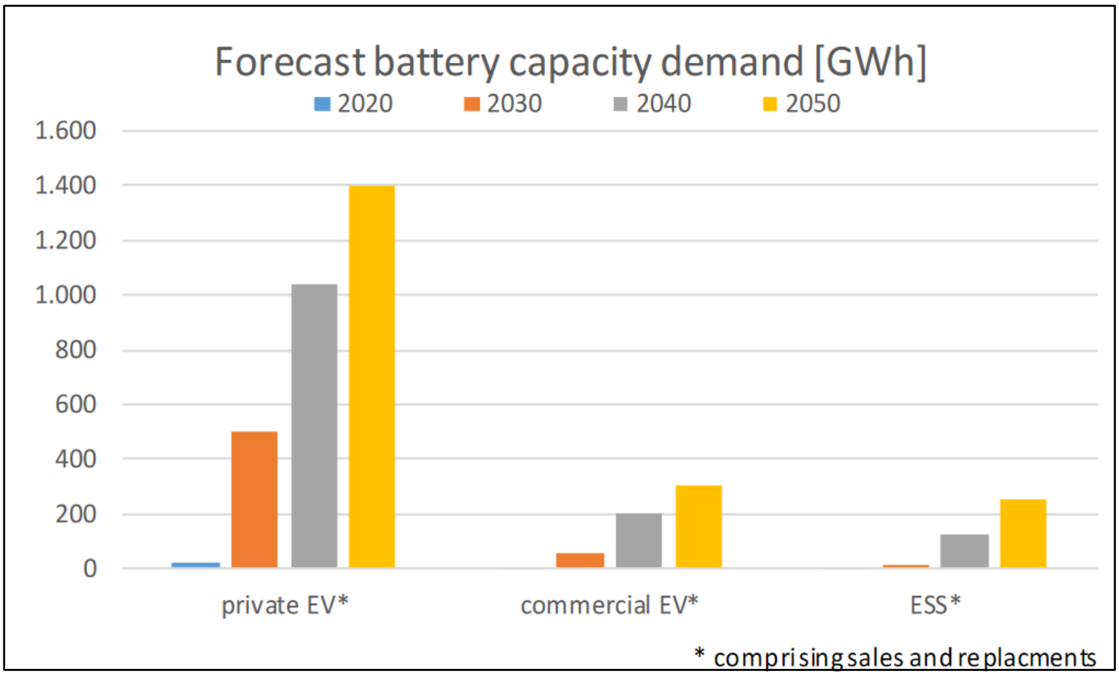

Figure 52: Estimated increase in battery capacity for passenger cars and commercial vehicles in addition to that of storage for stationary application (source: Ecodesign batteries)[57]

Repurposing in this context offers several advantages. In this way, part of the investment costs can be recovered and it also reduces the environmental impact because the batteries are only offered for recycling later, after their “second life”. Given the increasing sales and demand for electric vehicles, combined with a typical lifespan of 8 to 12 years, the supply of waste EV batteries can be expected to increase significantly in the coming years.

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[57] https://ecodesignbatteries.eu/sites/ecodesignbatteries.eu/files/attachments/EDB%20II%20Stakeholder%20Meeting%20Task%201_v2.pdf

## B.1 STATIONARY APPLICATIONS

The most obvious application for discarded EV batteries is in stationary storage systems, so-called Energy Storage Systems or ESS.

McKinsey[58] expects more than 112 GWh per year of storage capacity from "recycled" EV batteries to become available for grid-level stationary storage by 2030.

### UK ENERGY STORAGE LAB PROJECT

In the UKESL project[59], modules from spent batteries from 50 Nissan Leafs were tested and selected and placed in a pilot set-up. The storage capacity of the resulting storage system is 1MWh. For testing and selection, the Warwick Manufacturing Group developed a method that can characterize the modules in 3 minutes, based on Electrochemical Impedance Spectroscopy.

### NUVATION ENERGY STORAGE SYSTEM

Nuvation Energy built a 24 kWh storage system from used Nissan Leaf modules[60]. Since these had only 70% of the capacity, they were decommissioned but still suitable for stationary storage.

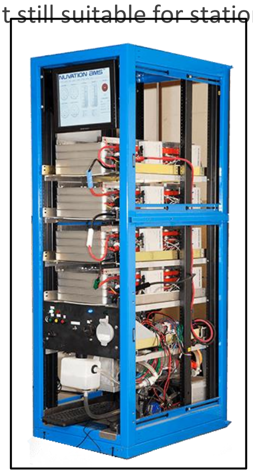

Figure 53: Nuvation storage system with Nissan Leaf modules

The system is smartly controlled to reduce peak consumption during the day, for example by charging EVs, which would otherwise entail additional costs. Charging takes place again at night when the energy price is lower.

### POWERVAULT

Powervault[61] develops and markets an energy storage system (PowerVault 3eco) for residential applications, based on used batteries from Nissan and Renault cars. The system is combined with an "EDF Grid Services" service, where the battery is also used to support the electricity network.

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[58] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

[59] http://www.element-energy.co.uk/wordpress/wp-content/uploads/2020/01/UKESL-Non-technical-Public-Report_2020.pdf

[60] https://www.nuvationenergy.com/nissan-leaf-second-life-ess

[61] https://www.powervault.co.uk

## BMW SPEICHERFARM LEIPZIG

In Leipzig, in 2017, BMW commissioned a stationary battery storage system[62] [63] based on 700 used BMW i3 battery packs. The system is operated within the WindNODE project, which explores the technical and economic potential of flexibility in the energy system to increase the share of renewable sources (such as from wind turbines).

Figure 54: BMW i3 batteries in the Speicherfarm Leipzig

## BENELUX

A number of initiatives have also been launched in the Benelux regarding the repurposing of (industrial) batteries. In the Netherlands, for example, ECarACCU[64] offers separate battery modules from demolition, in addition to mobile "generators" based on recycled modules and home batteries (under the ecolithium name). E-Powertower[65] does the same.

In Belgium, Watt4Ever[66] , Revolta[67] and Octave[68] , among others, want to use recovered EV batteries in stationary storage at companies.

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[62] https://www.press.bmwgroup.com/deutschland/article/detail/T0275547DE/bmw-group-demonstriert-fuehrungsrolle-im-bereich-elektromobilitaet?language=de

[63] https://www.automobil-produktion.de/hersteller/wirtschaft/bmw-speicherfarm-leipzig-soll-lukratives-geschaeftsmodell-werden-119.html

[64] https://ecaraccu.nl/

[65] https://www.e-powertower.nl/

[66] https://watt4ever.be/

[67] https://www.revolta.co/

[68] https://www.octave.brussels/

Figure 55: Modular home battery from E-Powertower

Figure 56: Watt4Ever 40kWh battery for the storage of PV energy

## B.2 BUFFER FOR FAST CHARGING STATIONS

Since fast-charging stations for EVs are becoming increasingly powerful (>100kW), the charging speed of individual charging EVs sometimes has to be reduced if there is a risk of local overloading of the network connection. Some manufacturers[69,70,71] therefore offer solutions in which a stationary battery can be used as a buffer, also known as peak shaving. The battery is charged slowly from the mains, then provides the short but higher powers when cars charge quickly. Car manufacturers such as Tesla[72] and Porsche[73] have also come up with such solutions.

Figure 57: Mobile fast charging station from Porsche for track days

Figure 58: Buffer battery for fast charger in Spain with recycled EV batteries

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[69] FreeWire's Boost Charger, https://freewiretech.com/products/dc-boost-charger/

[70] ABB to use AFC Energy's off-grid DC charging solution, https://www.electrive.com/2020/12/17/abb-to-use-afc-energys-off-grid-dc-charging-solution/

[71] https://www.irizar-emobility.com/the-first-charging-station-for-electric-vehicles-using-second-life-batteries-from-irizar-e-mobility-is-in-service/

[72] Tesla deploys mobile EV superchargers – powered by new Megapack battery, https://thedriven.io/2019/12/02/tesla-deploys-mobile-ev-superchargers-powered-by-new-megapack-battery/

[73] High-power charging trucks become mobile power sources, https://newsroom.porsche.com/en/2020/company/porsche-high-power-charging-trucks-mobile-power-sources-22285.html

### B.3 REFURBISHMENT AND REPAIR

The most ecological thing is of course to extend the life of the 1st application as much as possible. Sometimes this can be done by repairing or refurbishing battery packs, by replacing broken parts or modules. Nissan, for example, sells upgraded packs[74] to owners of old Leafs whose battery capacity has dropped too far. It also itself uses old Leaf cells in the autonomous vehicles (AGVs) that deliver parts in their factories[75], which it claims drastically reduces maintenance compared to lead-acid batteries.

Renault mainly uses a leasing model for their electric models, which means that the battery remains fully owned by the manufacturer. When the capacity has dropped below 75%, it is replaced and the old battery may be used for a second life, such as electric touring boats[76].
Renault also claims that it is capable of repairing defective batteries.

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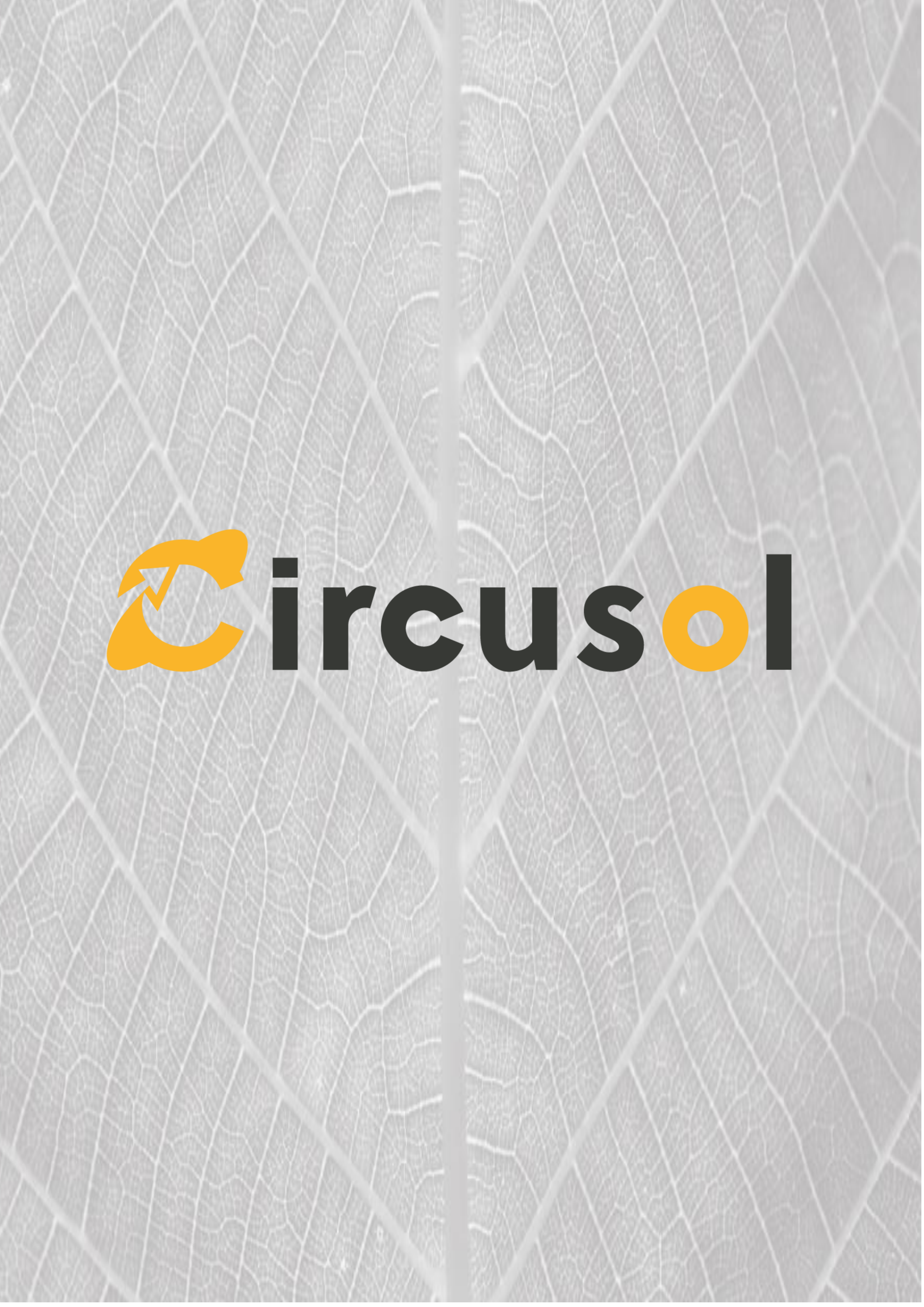
[74] https://insideevs.com/news/337360/nissan-introduces-2850-refabricated-batteries-for-older-leaf/
[75] https://usa.nissannews.com/en-US/releases/the-leafs-lithium-ion-batteries-find-a-home-in-nissans-automated-guided-vehicles
[76] https://electrek.co/2019/11/12/electric-boat-used-renault-zoe-battery-packs-paris/



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