



Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1

TASK 4

Technologies – For Ecodesign and Energy Labelling

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- Version made available in December 2018 for the Stakeholders to comment and discussion in the stakeholder meeting.

Version 2:

- is a review based on the input from the stakeholder comments which resulted mainly in a reviewed description of the technology itself and the life cycle stages
- includes several updates on the text and additional figures
- revised version of the BOM according to the stakeholder comments
- includes some recommendations based on the findings of this task at the end of the report.

Version 3:

- Additional information provided for the BOM
- Additional data provided on recycling rates
- Literature sources revised

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ABBREVIATIONS

Abbreviations	Descriptions
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by Road
Al	Aluminum
BAT	Best Available Technologies
BC	Base case
BEV	Battery Electric Vehicle
BJB	Battery junction box
BMS	Battery Management System
BNAT	Best Not-yet Available Technologies
BOM	Bill-of-Material
CED	Cumulative energy demand
CMC	Carbon methyl cellulose
CNT	Carbon nanotube
Co	Cobalt
CPE	Composite polymer electrolytes
CRM	Critical Raw Materials
DEC	Diethyl carbonate
DMC	Dimethyl carbonate
DOD	Depth of Discharge
EC	European Commission
EC	Ethylene carbonate
EMC	Ethyl methyl carbonate
EoL	End-of-life
EPTA	European Power Tool Association
ESS	Electrical Energy Storage Systems
EU	European Union
EV	Electric Vehicle
Fe	Iron
FU	Functional Unit
GWP	Global Warming Potential
HE	High-energy
HEV	Hybrid Electric Vehicle
HV	High-voltage
IATA	International Air Transport Association
IMDG	International Maritime Dangerous Goods Code
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCO	Lithium-ion Cobalt Oxide
LCV	Light commercial vehicles
LFP	Lithium-Ion Phosphate
Li	Lithium
LIB	Lithium ion battery
LMNO	Lithium-Ion Manganese Nickel Oxide
LMO	Lithium-Ion Manganese Oxide
LMP	Lithium-Metal-Polymer

LTO	Lithium-Ion Titanate Oxide
LVD	Low Voltage equipment
MEErP	Methodology for Ecodesign of Energy related Products
Mn	Manganese
NCA	Lithium Nickel Cobalt Aluminium
Ni	Nickel
NiCd	Nickel-Cadmium
NiMh	Nickel-Metal hydride
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
P	Phosphor
Pb	Lead
PC	Passenger car
PE	Polyethylene
PHEV	Plug-in Hybrid Electric Vehicle
PP	Polypropylene
PV	Photovoltaic
PVD	Physical vapour deposition
R&D	Research and Development
SASLAB	Sustainability Assessment of Second Life Application of Automotive Batteries
SEI	Solid-electrolyte interphase
Si	Silicon
SOC	State of Charge
SPE	Solid polymer electrolyte
TIM	Thermal interfacial material
TRL	Technology Readiness Level
UN	United Nations
UNECE	United Nations Economic Commission for Europe
WEEE	Waste electrical and electronic equipment
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie e. V.

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4. Task 4: Technologies

Summary

Battery systems are built up on a range of cells technologies, which are evolving rapidly in order to improve efficiency, energy density, performance or reliability. Furthermore, improvements on component side as e.g. the housing or BMS (Battery Management System) allow a broad spectrum of different combinations to design a battery system. Anyhow, taking as a reference year 2018, the lithium-ion technology can be expected a suitable base case, for applications as battery-electric passenger car (PC BEV), plug-in-hybrid passenger car (PC PHEV), battery-electric light commercial vehicles (LCV BEV), battery-electric medium-duty tractor unit (Truck BEV), plug-in-hybrid heavy-duty tractor unit (Truck PHEV), Residential storage and Grid stabilization.

Furthermore, lately a number of competing lithium-ion cell chemistries and designs have subsequently been commercialized and could be candidates for Best Available Technologies (BAT). These comprise cells, which use cathodes, with a higher content of Ni or which are renouncing on using a blend of materials. While e.g. for the anode a percentage of silicon is added to the former pure graphite anode. However, new cell technologies are evolving as for example high voltage spinel, high energy NMC (Nickel Manganese Cobalt Oxide) or Ni-rich cathode materials as well as solid-state batteries¹. Those, also not yet available on the market can be considered for Best Not-yet Available Technologies (BNAT).

Current batteries on the market are not designed for circularity, meaning easy to disassemble, repair, refurbishment and recycling. They are not considered to be easily opened and usually designed to be only opened at end of life by mechanical intervention. Such irreversible design severely limits not only the potential for repair/refurbishment potentials, but also the recovery of valuable materials or the reuse of components. There are only currently limited examples of module design to support ease of disassembly or dismantling for recycling.

Despite of the outstanding needs from recyclers and of the advancements in technological research, there are currently a clear lack of business incentives for manufacturers to implement design-for-circularity.

In summary, the following Base cases (BC), BAT and BNAT were identified². The cell technology is proposed as starting point for defining the combinations because it is fundamental to achieving performance improvements. Therefore, it has to be considered that we are dealing with a flexible product, consisting of different cell chemistries.

- The Base Case e.g. (BC1) is an average performing EV battery system for BC1.
- A BAT Case is combining one or more measures as listed in Table 2 (see chapter 4.1.3) for "Today"
 - Higher share of Ni (in case of NMC but not already NMC 811 Ni-rich).
 - Silicon added graphite anode and an increased layer thickness compared to previous versions of the cells.
 - Reduced thickness of the separator

¹ Other than LMP

² An in-depth analysis of the base cases will be conducted in Task 5

- Optimization of inactive materials: Reduction of inactive materials such as binders, or the reduction of current collector thickness.
- Housing improvements regarding isolation, weight and more.
- BNAT- is a battery system based on future improvements (see 4.1.3), thus the BNAT is expected to include battery technologies as:
 - All-solid-state batteries
 - High-voltage spinels or
 - High energy NMC

4.1. Subtask 4.1 - Technical product description

Task 4 provides a technological description of the products in scope of the study. Thus, it serves two different purposes: On the one hand it is intended to inform the policymakers and stakeholders about the product and its components from a technical perspective, on the other hand it serves to define the Base Cases and also works towards the definition of Best Available Technology (BAT) and state-of-the-art Best Not yet Available Technology (BNAT). While the Base Case represents an average product on the market today in terms of resources efficiency, emissions and functional performance, the BAT and BNAT will also be assessed in terms of environmental improvement potential. The BAT represents the best commercially available product with the lowest resources use and/or emissions. The BNAT represents an experimentally proven technology that is not yet brought to market, e.g. it is still at the stage of field-tests or official approval. The assessment of the BAT and BNAT provides the input for the identification of the improvement potentials in Task 6. The data for the base cases will serve as input for Task 5.

4.1.1. Existing products

4.1.1.1. Description of the key components of a battery system

A battery system builds up from different subcomponents, which are depicted in the following Figure 1. The electrode is thereby often seen as the smallest joint unit within a battery system.

A cell contains, depending on its final purpose, a certain number of electrodes. Since, the energy of a single cell is in most cases not sufficient for performing the function of a product; several cells are connected in parallel or in series to form modules. The individual modules are then provided with a mechanical support structure and connectors. Several modules in a row or in parallel are then combined again to form a battery system. The number and type of connected cells and modules finally depends on the desired operating mode of the application (Ketterer et al. 2009).



Figure 1: Schematic overview of the key components of a battery system after (Hettesheimer 2017)

In order for the cell or battery system to fulfil its intended function safely and optimally, further additional components are required on battery system level. The housing with the associated cooling system and battery management system shields the partially sensitive active and passive components of the accumulator system (BMS) from harmful environmental influences (water, dust, etc.) (Rahimzei et al. 2015).

After giving this short overview of the structure of a battery system, a detailed description of the mentioned key components will be given in the following.

4.1.1.2. Key components on cell level - Elements of a cell and cell formats

The components of a battery cell that are needed to fulfil its function are the cathode, anode, separator, electrolyte and the housing as well as further safety components. The functional structure of a cell and of the key components is exemplarily displayed in the following Figure 2. The components will be briefly described while an outlook of their future improvement potentials will be given later.

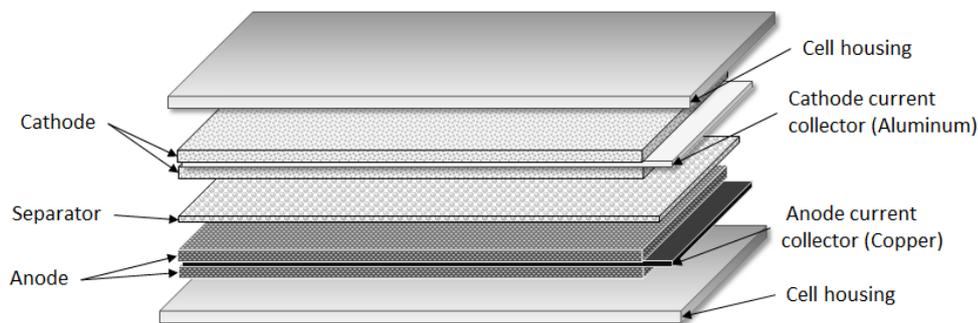


Figure 2: Exemplary structure of a battery cell (Hettesheimer 2017)

Cathode

The cathode (positive electrode) consists of mixed oxides applied to an aluminium foil (or aluminium current collector). The cathode material consists of the active material, a polymeric binder which is usually polyvinylidene difluoride and a conductive additive as carbon black. The cathode materials currently used are lithium nickel cobalt manganese oxide (NMC), lithium nickel cobalt manganese oxide (NCA) or lithium iron phosphate (LFP). In addition, these cathode materials are also mixed with lithium manganese oxide (LMO) to form LMO-NCM and LMO-NCA (Thomas et al. 2018; Rahimzei et al. 2015).

Manganese spinel oxides (LiMn_2O_4 , LMO for short) are characterized by high safety in the event of overcharging, high thermal stability and low material costs. Their specific capacity is about 120 mAh/g. Difficulties arise due to undesired side reactions, like Mn dissolution, which lead to a reduction in service life.

Lithium nickel cobalt aluminium oxide (LiNiCoAlO_2 , NCA for short) has a high power density and long service life as well as a high specific capacity of 160-180 mAh/g. Disadvantages are the low thermal stability as well as high material costs, whereby depending on the development of nickel and cobalt prices there is still price reduction potential.

Compared to NCA, lithium nickel manganese cobalt oxide (LiNiMnCo_2 , NMC for short) is characterized by higher thermal stability and lower costs, while the specific capacity of 150 mAh/g (NMC 111) is somewhat lower. Compounds with a higher share of Ni as NMC 532 are achieving a higher energy density of somewhat 170 mAh/g. Furthermore, there are also

chemistries with still higher energy capacities available and under development, which will be described later on.

The lithium iron phosphate batteries (LiFePO₄, LFP for short) have a higher chemical stability than the oxides. This ensures a long service life and safety³. It is also environmentally friendly and relatively inexpensive. The specific capacity is approx. 160 mAh/g and thus roughly corresponds to that of NMC, but at lower voltage of 3.3 V (Anderman 2013; Mock 2010; Wallentowitz and Freialdenhoven 2011; Peters et al. 2013).

The following table provides a summary of the properties of different cathode materials.

Table 1: Properties of different cathode materials (Rosina 2016)

	LMO	LFP	NMC	LTO	NCA
Nominal voltage	3.80 V	3.30 V	3.65 V	2.3 V	3.60 V
Charge limit (Vmax)	4.20 V	3.60 V	4.20 V	2.7	4.20 V
Cycle life	>1000	>2000	1000 -2000	>5000 Up to 15 000+	2000 -3000
Specific power (W/kg)	Medium/high	Medium/high	High	High	High
Thermal stability	Fairly stable	Stable	Fairly stable	Stable	Least stable
Cost	Medium	Medium-to-high	Medium-to-high	High	Medium-to-high
Pros	<ul style="list-style-type: none"> •Cost •Safety •Power 	<ul style="list-style-type: none"> •Safety •Materials cost •Life expectancy 	<ul style="list-style-type: none"> •Energy density •Range of charge 	<ul style="list-style-type: none"> •Safety •Cycle time 	<ul style="list-style-type: none"> •Energy density •Lifetime
Cons	<ul style="list-style-type: none"> •Lifetime 	<ul style="list-style-type: none"> •Low temp. performance •Processing cost 	<ul style="list-style-type: none"> •Safety •Cost 	<ul style="list-style-type: none"> •Low voltage •Energy density 	<ul style="list-style-type: none"> •Cost •Safety •Low thermal stability
Supplier	LG, Chem, Samsung SDI, AESC	BYD, A123, Saft	Panasonic, Kokam, Saft	Leclanché, Toshiba, Microvast, ATL	Panasonic, Saft

³ Under the prerequisite that the cell is also constructed in a safe manner.

Anode

The anode (negative electrode) of the typical li-ion cell consists of a copper foil (or copper current collector) and graphite or a lithium alloy material. Natural or synthetic graphite anodes are currently the most common choice because of their low electrode potential and low volume expansion when Li^+ ions are intercalated. For high performance and safety requirements, lithium titanate as an additional option is also available, going along with disadvantages in terms of cost and energy density. Common binders here are: e.g. carbon methyl cellulose (CMC) or polyacrylic acid (Rahimzei et al. 2015). In the case of an all solid Lithium-Metal-Polymer (or LMP®) cell, the anode is made of a thin film of metallic lithium that serves simultaneously as an electrochemical anode and a current collector

Separator

The LIB separator isolates the two electrodes from each other in order to prevent a short circuit and to prevent malfunctions. The pores of the separator are filled with the electrolyte in liquid or gel form. The separator is mostly made of a porous plastic composite of polyethylene (PE) and polypropylene (PP). But PP/PE has the disadvantage of a low melting temperature (approx. 165 °C). However, another choice to enhance thermal resistance, are ceramic or ceramic coated separator. In addition, nonwovens and glass fibre separators are used in research (Rahimzei et al. 2015). For the LMP technology, the separator is a thin polymeric film that contains the lithium salt. It serves simultaneously both the purposes of separator and electrolyte.

Electrolyte

Electrodes are wetted by liquid electrolyte, which enables Li-ion transport. The electrolyte is required to be stable electrically in a typical LIB voltage range from 0 to 4.5 V and must have a high ion conductivity over a wide temperature range (from -40 °C up to +80 °C). Usually a liquid electrolyte consists of mixture solutions such as ethylene carbonate (EC), diethyl carbonate (DEC), dimethyl carbonate (DMC), and ethyl methyl carbonate (EMC) dissolved lithium salts (e.g. LiPF_6). Besides the most common fluid electrolyte, also polymer electrolytes are used. Since it is not possible for the polymers to escape, the use of stiff containers is not necessary and thus a lighter construction possible. The disadvantage, however, is the lower conductivity (Rahimzei et al. 2015; Thomas et al. 2018).

4.1.1.3. Cell housing and cell formats

Li-ion cells differ not only in the cell chemistry used, but also in their cell geometries, which directly influence the shape of the cell housing. Currently, three different cell formats are used in practice: the cylindrical cell, the pouch cell and the prismatic cell.

The basic elements of a cell described in Figure 2 represent the starting point of any cell geometry. Depending on the shape of the cell housing, the cell is inserted differently into the housing during the production step of cell assembly. While pouch cells can be stacked or wound, cylindrical and prismatic cells are usually wound. The different cell shapes as well as a cross-section (A, B & C) of the respective cells are illustrated in Figure 3.

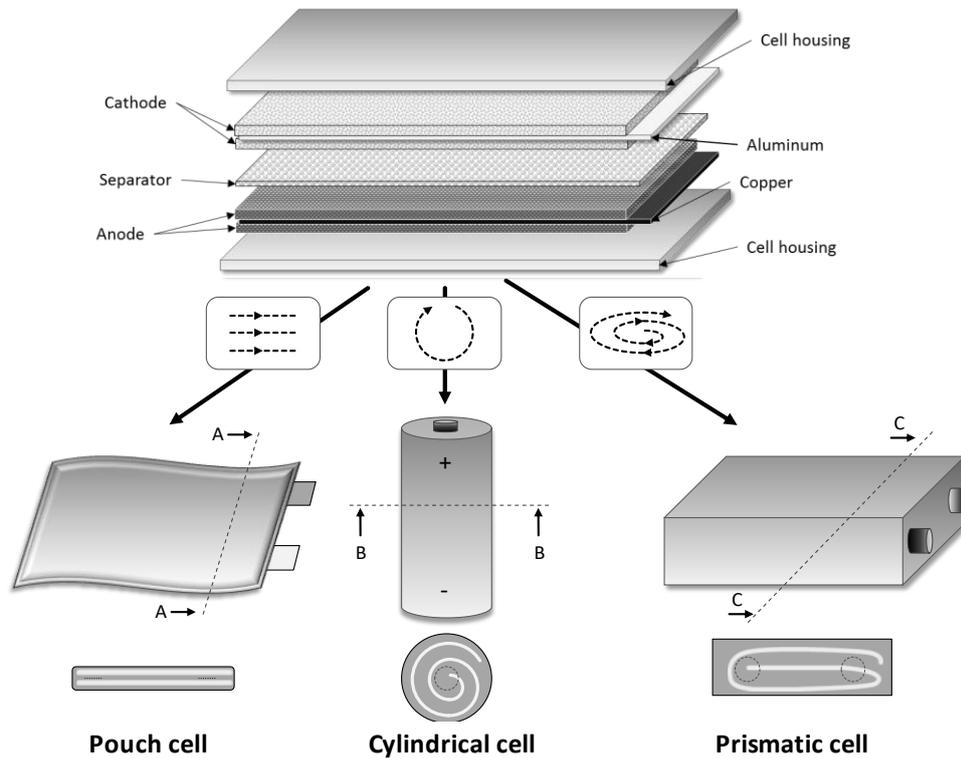


Figure 3: Possible cell formats: pouch, cylindrical and prismatic cell format

Depending on the geometry used, the cells have different advantages and disadvantages. The highest volumetric energy density of cylindrical cells is due to the basic geometry highest, but the energy density of large-format pouch cells has approached or reached a similar energy density to that of small-format lithium-ion cells in recent years. Depending on the module design, the cylindrical cell loses some of its advantage over the prismatic and pouch cell at the module level due to the packing density. The stiffness of the cylindrical cells is regarded as highest. A middle way trade-off between stability and size is the prismatic cell, which is produced with the help of a flat winding, similar to the cylindrical cell, and then inserted into a solid housing. With the pouch cell, the stiffness is not given by the pouch foil and must be supplemented with a frame when inserted into the module. All three cell shapes can be well thermally controlled. The main differences lie in the necessary cooling effort and the possibilities of dissipating and conducting heat. The pouch cell enables good heat dissipation via the current collectors and thus offers the best cooling performance. In the cylindrical cell, the heat generated in the core during charging processes can only be dissipated to a limited extent via the cell housing and the cell lid. This disadvantage can also be seen by the prismatic cell format. These are commonly cooled via the bottom, whereby cooling between the prismatic cells is also conceivable (Michaelis et al. 2018; Hettesheimer et al. 2017).

The pouch cell material is an aluminium-polymer composite that forms a soft cell container. Cylindrical and prismatic cell containers are hard cases. Cylindrical cell containers are commonly made of steel or aluminium, while prismatic cell containers are made of polymers or aluminium (Thomas et al. 2018).

4.1.1.4. Key components on module level

Even though the formats of the cells are geometrically very different, the outer appearance of a module for prismatic or a pouch cells looks quite similar (see Figure 4). The type of components on module level are also more or less the same (also the number of the specific

components installed may differ). The cells are stored in a casing to provide them mechanical support. The casing is thereby mostly made of aluminium or PP/PE. Furthermore, the cells are connected on the tabs by busbars, mostly made of aluminium. For temperature, regulation sensors are applied and cooling channels provided. Finally, each module has terminals to interconnect it with other modules.

Prismatic format (Source: Audi)

Pouch format (Source: Audi)

Cylindrical format (Source: Panasonic)

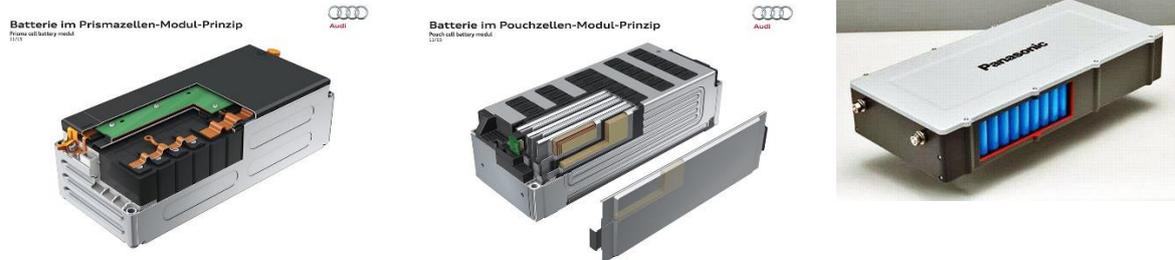


Figure 4: Exemplary module structures for different cell formats

4.1.1.5. Key components on system level

Battery management system (BMS)

The task of the battery management system is the intelligent and optimised operation of the battery, which increases the service life, reliability, safety and economy of the battery system. For this reason, various sensors for temperature, voltage or current measurement are integrated in the individual modules. The current battery condition, also known as "State-of-Charge" (SOC), can be derived from this. And, for example in the case of EV, conclusions can be drawn about the remaining range of a vehicle based on the SOC. A further important task of the BMS is the charge and discharge control, since extreme imbalances between the cell charge states could occur during the respective processes without targeted control, which would make it impossible to charge the serially following cells again. For optimum service life and operation, it is therefore necessary to balance the cells. As part of safety management, short circuits are detected and battery operation is prevented by a safety circuit. Ultimately, the battery management system is also responsible for operating the battery in its optimum temperature range and the associated thermal management. According to Majeau-Bettez et. al. the BMS contains electronic circuits, software, and internal/external connections as well as wires used to operate the battery. The BMS consists of approximately 10% printed wire (circuit) boards, 40% steel, and 50% copper by weight (Majeau-Bettez et al. 2011b).

Thermal management

In lithium-ion batteries, thermal management has the task of controlling cell temperature efficiently and reliably, since cell performance and ageing are strongly dependent on temperature. Increased temperatures lead, for example, to faster degradation of the materials and faster aging of the battery. If not controlled, higher temperatures may also lead to the triggering of a thermal runaway phenomenon⁴. Low temperatures can lead to an obstruction

⁴ In the case of all-solid LMP cells, safety concerns are raised only when cell temperature reaches the melting temperature of lithium at 180°C. On the contrary they need to be operated at a minimum temperature of 60°C or more depending on the ionic conductivity that the application requires.

of the current flow, as the conductivity in the electrolyte is reduced. The system may therefore be cooled at high temperatures or heated in colder weather conditions to ensure normal operation, optimum power output and service life. Depending on the application, both functions can have considerable effects on the total power consumption and thus e.g. in the case of EV on the purely electrical range. The cooling system is either operated with air, water or other liquid coolants as e.g. Ethylene-Glycol and is often based on a heat-pump system for also cooling or heating the cabin. Furthermore, a TIM (Thermal interfacial material) is also used between cell and pack bottom. The cooling system consists mainly of aluminium and partly of steel. The aluminium radiator is thereby the main component (Rahimzei et al. 2015; Hettesheimer 2017; Ellingsen et al. 2014).

Housing and additional components

As described above, the housing shields the active and passive components of the battery system, from harmful environmental influences. It also shields service personnel from high-voltage components and provides temporary fire protection. It is therefore crucial for safe, reliable and long-term operation. Especially in the case of EV traction batteries, which are usually housed in the floor area of the vehicle, the housing may be exposed to extreme influences such as rockfall, splashing water, etc. High mechanical stability and corrosion resistance are therefore important. When designing the battery system for EV, attention must be paid not only to the housing but also to internal and external mounting systems, which must be able to withstand the sometimes high mechanical and thermal loads. In addition, the housing, together with the components contained therein, also serves as a stabilizing element for the body of some "Purpose Design" vehicles. Since the housing must not only offer a high protection but has to be light weighted too, it is usually made of aluminium and/or PP/PE.

In addition to the components mentioned above, there are numerous other elements to complete the battery system. Busbars connect the modules together and fuses protect the components from damage due to power surge or contactors which are isolating the battery system from the vehicle. Closed upon completion of safety tests and opened in the event of a crash or battery fault (Rahimzei et al. 2015).

4.1.2. Discussion on battery technology improvement (design) options

Defining standard improvement options for battery systems in the sense as for other products listed in the Ecodesign working plan is quite difficult. Since the LiB was continuously improved in the past years it can already be considered as a quite mature product and a thus standards improvement options are already state-of-the-art. Anyhow, improvements were mostly made on the component level and regarding the efficient operation of the battery. Potential may still be found in the engineering of the battery; e.g. LG was able to increase the energy density of its cell by 50% without changing the chemistry (Rosina 2016). Another major point of improvement is the reduction of passive components and materials within the cell and the system to reduce the weight, material content and thus reduce the environmental impact and increase the energy density. This can be reached by using thinner conductors or separators, reducing the dead volume within the cell or by using lightweight components for the battery tray (Takeshita et al. 2018; Thielmann et al. 2017).

However, in the upcoming years some relevant improvements are expected regarding Li-based batteries other battery types as for example non-polymeric all-solid-state batteries using metallic lithium. To define a BAT and a BNAT it is necessary to take a closer look on the future development prospective by means of the different battery components. This procedure differs from MEErP in which sections on standard improvement, BAT and BNAT are usually described in sequence. Anyhow, in this specific case for battery systems it seems rather

expedient to focus on components and their improvement potentials. Based on this, subsequently a classification regarding BAT or BNAT can be made. A quite detailed outlook on the developments on component level is given by means of a roadmap from (Thielmann et al. 2017) which was developed under cooperation of German actors from science and industry and is listing mayor improvement options until the year 2030. In the following Figure 5 different technological developments and therefore improvement, options will be described for the different system components until the year 2025. The study will thus include Li-ion technologies up to generation 3b (as e.g. high voltage spinel cathodes or carbon-silicon anodes).

Preparatory study on Ecodesign and Energy Labelling of batteries

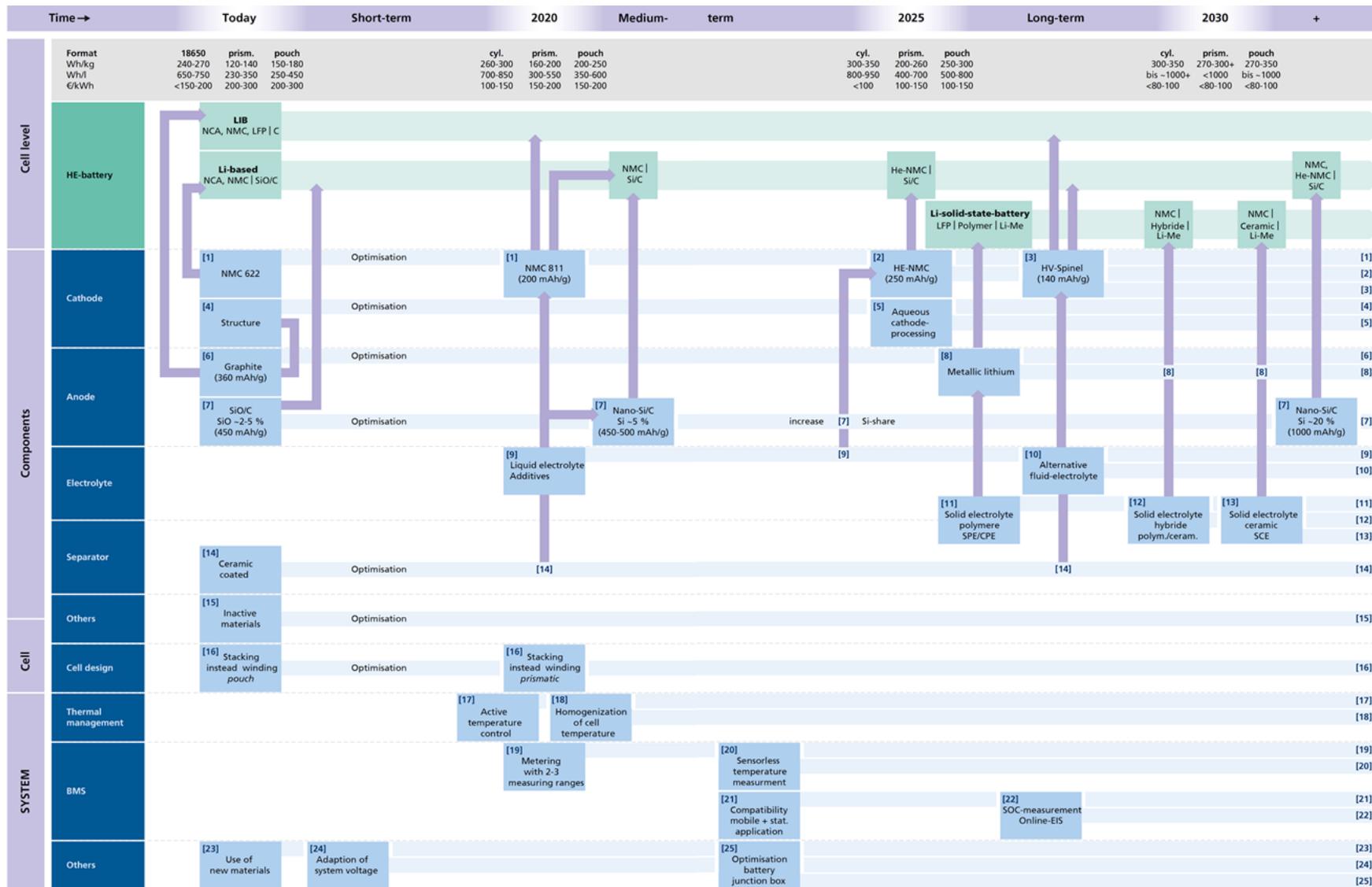


Figure 5: Definition of improvement options (Thielmann et al. 2017)

The classification regarding BAT and BNAT will be made after the description of the improvement options in Table 2 (in section 4.1.3).

4.1.2.1. Cathode⁵

4.1.2.1.1. Nickel-rich materials

Nickel-rich materials are defined as NCA with more than 80% nickel, or NMC with a composition of 811.

Target and suitable cell formats

The aim of using nickel-rich materials is, on the one hand, to dispense with Co or at least to reduce the Co content of the active materials. This leads to a reduction in material costs and resource requirements. On the other hand, it also results in an increase in material performance, as the electrical conductivity and Li⁺ diffusivity increase with an increased Ni content.

Bottlenecks and solutions

The central bottleneck for reaching market maturity is an increase in the service life of the materials. However, this can be achieved with a low to medium R&D effort. This is analogous to what has already happened with NMC materials such as 532 or 622, which now represent the state of the art. The reason for the reduced service life is that the surface of the nickel-rich materials is more reactive to the electrolyte (the unreacted residual Li source on the cathode surface can react with the binder to make gelation during slurry mixing process). Coatings, for example, can be a solution to this problem and for protection of crack and cation mixing causing new surface areas with structural unstable weakness of High Ni cathode. In addition, care must be taken during processing to ensure that the room humidity < 50% is maintained.

Advantages and disadvantages

Extremely high energy densities can be achieved with nickel-rich materials, as these materials or powders can theoretically be compacted almost to the level of LCO. Co-free materials have a higher electrical conductivity compared to NMC 111. This offers the possibility to save conductive additives and thus to reduce the inactive part in the cathode or to save further costs. Overall, the costs (per kWh) are considerably lower than with state-of-the-art systems or NMC 622.

Furthermore, the approach provides an advantage with regard to resource availability, especially with regard to cobalt which is classified by the EC as a critical raw material⁶. On the other hand, the higher moisture sensitivity is disadvantageous compared to NMC standard materials. However, this is still at a manageable level, although production costs are rising.

Effort and producibility

Producibility goes hand in hand with minor adaptations.

Maturity and market entry (in automotive application)

The approach is currently still in the range of prototypes to demonstration. First samples can however already be sampled by the customer. The market maturity for nickel-rich materials

⁵ The following improvement options are based on Thielmann et al. 2017. For this reason the source will not be listed after each abstract.

⁶ <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0490>

(NMC 811) is expected to be reached around 2020. Thus, this approach can be classified as BNAT or even BAT.

4.1.2.1.2. High-energy NMCs

High-energy (density) NMCs are lithium-rich "integrated" composite materials which can be defined as $y \times \text{Li}_2\text{MnO}_3$ $(1-y) \times \text{LiMO}_2$ $M = (\text{Ni}, \text{Mn}, \text{Co})$. The materials offer a theoretically high specific capacity due to an advantageous ratio of Li to transition metal with greater than 1.

Aim and suitable cell formats

In practice, specific capacities of about 280 mAh/g are currently being achieved. The use of high-energy NMC thus aims to increase energy density. Furthermore, high energy NMC has a price advantage over nickel-rich materials due to its high Mn content and thus offers additional cost reduction potential. The cell format plays no role for the use of high-energy NMC.

Bottlenecks and solutions

Bottlenecks currently form the electrolyte availability as well as the electrolyte costs, which are comparatively high as standard electrolytes are no longer sufficient. Furthermore, the washing out of Mn can also impair the service life of the materials. Mn precipitates in the cell and the cathode material degrading its performance. Particle coatings are a possibility to prevent the washing out.

Advantages and disadvantages

There is a very high cost advantage at cell level due to the high Mn content. In addition, the energy density is better than with NMC-111 systems, but lower than with nickel-rich materials. The porosity of the powders, on the other hand, is similar, although the intrinsic density is lower, which results in a lower overall density in the comparison with nickel-rich materials. Thus high energy NMC is very advantageous in terms of cost, but not the best solution in terms of high energy densities. The use of high-energy NMC therefore also depends on the application and the available installation space, as well as on how much one is dependent on the high energy densities.

Apart from this limitation, electrode balancing with the anode is problematic (different specific capacities of cathode and anode). The anode would have to be very thick to completely absorb the lithium from the cathode. However, this in turn limits performance and has a negative effect on producibility. However, this aspect can be largely compensated by the use of silicon-containing anodes.

Effort and producibility

For the use of HE-NMC a higher R&D expenditure has to be considered until the product is finally ready for the market. This also concerns the producibility, for which a small expenditure can be assumed.

Degree of maturity and market entry

At present the manganese-rich materials are still in the area of applied research up to prototypes, possibly already with the customer sampling. The market entry of High Energy NMC could take place in the year 2025 provided that all difficulties are overcome. Thus, this approach can be classified as BNAT but may be out of time scope.

4.1.2.1.3. High-voltage spinels

High-voltage spinels are lithium-manganese based oxides with a cubic structure. As nickel doped oxides, they are classified as "5V" materials (e.g. $\text{LiMn}_{1.5}\text{Ni}_{0.5}\text{O}_4$, 4.8V against Li/Li⁺). The capacity of the high-voltage spinel is approximately 140 mAh/g.

Target and suitable cell formats

The material is comparatively well available and inexpensive, which can result in cost advantages. At the module level, a smaller number of cells can be used to achieve a high battery voltage, thus reducing costs and increasing energy density if necessary. As with the approaches already mentioned, the use of high-voltage spinels is independent of the cell format.

Bottlenecks and solutions

Challenges on the way to market maturity relate in particular to electrolytes. The electrode materials are rather unstable at this high voltage operation. Mn is dissolved into the electrolyte and accumulate on anode surface during charging as side products by reaction with electrolyte. The central bottleneck is therefore cathode material stability, electrolyte stability and manganese leaching. The electrolyte stability causes the decomposition products of the electrolyte to deposit on graphite anodes and continue to react. This ultimately leads to cell death through dendrite formation and possible punctuation of the separator or faster degradation the cell performance.

The electrolyte thus has a significant influence on the service life of the cell. State-of-the-art carbonate-based electrolytes are stable up to about 4.5 V against Li/Li⁺. This stability must therefore be further increased in the future, since e.g. High voltage - NMC requires a stability up to 5 V against Li/Li⁺. Alternatively, coatings for these active materials are also being developed to compensate for these disadvantages.

Advantages and disadvantages

A major advantage of using high-voltage spinels is the price advantage for the cathode material resulting from the elimination of cobalt and the high proportion of manganese in combination with the higher average voltage compared to standard NMC. In addition, the energy density can be increased compared to conventional anode materials due to the possible high potential. However, not at the level of nickel-rich materials. The disadvantage of using high-voltage spinels is the availability of suitable electrolytes and the separator stability.

Effort and producibility

The R&D expenditure of this approach is to be classified as high. The adjustments to producibility are rather small or even drop-in capable.

Maturity level and market entry

HV technology is currently in the field of applied research. The market entry of high-voltage spinels could take place between 2025 and 2030. Thus, this approach can be classified as BNAT but is out of time scope of this study.

4.1.2.1.4. Layer thickness

With regard to the layer thickness, the optimization of the electrode is not considered from the raw material perspective, but from the conceptual point of view of how the electrode is designed. The charge of a cathode is currently around 40-100 Ah/m² (coated on both sides with aluminium). The central influencing variables for an increase in energy density are layer

thickness, porosity and tortuosity. The layer thickness influences the processability, flexibility, stability and thus also the service life of the cell. In addition, high layer thicknesses impair the thermal conductivity of the electrode. Passivated (isolated) areas can form and drying becomes more time-consuming. The tortuosity can be changed by micro-structuring the electrode accordingly. The porosity is currently even worse than hexagonal closest ball packing, while the total density is already close to the limit, as the conductive additive and the binder are still required.

Aim and suitable cell formats

The general goal of an increased layer thickness of active materials is to increase the energy density by increasing the ratio of active to inactive materials. The approach of increased layer thicknesses is in principle suitable for all cell formats.

Bottlenecks and solutions

The most important bottleneck on the way to an increased layer thickness is the difficult processability. Increasing the layer thickness in order to obtain a few percent more energy density at the system level already leads to a considerable increase in expenditure. Accordingly, further development activities must be undertaken in the area of processability (e.g. with regard to the drying of thick layers, powder coating processes, the handling of the thicker electrode, for example when winding through the thicker bending radii, when filling, etc.). Another bottleneck is the usable capacity of thick layers. The thickness has a negative effect on conductivity and electrolyte distribution, which means that it takes much longer to supply the cathode material with lithium ions or to transport them away.

Advantages and disadvantages

The advantage lies in the higher energy density due to the configuration of the electrodes and the relatively lower proportion of inactive materials. The disadvantage, however, is the poorer processability due to the reduced mechanical flexibility. The lower conductivity of thick material layers leads to a poorer fast charging capacity of the cells. Furthermore, also the available power at a low SOC will be affected. Active materials with increased layer thickness are already on the market, and the approach is constantly being further developed.

Effort and producibility

The effort required to optimize the layer thickness can be regarded as high, the adjustments to the producibility as low.

Maturity and market entry

The maturity is to be seen between the applied research up to the prototype. Approaches to optimizing layer thickness are already state-of-the-art today and will continue to be pursued and continuously improved in the future. Thus, this approach can be classified as BAT.

4.1.2.1.5. Aqueous cathode production

Aqueous cathode production describes the substitution of organic solvents by water.

Aim and suitable cell formats

The aim of using aqueous media during electrode manufacturing is to reduce manufacturing costs and to make LIBs much more environmentally friendly by eliminating the use of organic solvents. Aqueous cathode production is suitable for all formats.

Bottlenecks and solutions

An essential bottleneck lays in the quality of aqueous electrodes/cells and their electrochemical performance. Many of the cell components, such as highly nickel-rich systems or the electrolyte, are very sensitive to water. Even small residual amounts in the ppm range can have a significant effect on the performance and service life of the cells. The processability can also still be regarded as difficult at present, as there is no corresponding process route in place to allow the water supplied during processing to be completely dried out of the electrodes again. One solution on the material side would be to hydro-phobize the material, which is, however, very costly.

Advantages and disadvantages

The advantage of an aqueous cathode production lays in the reduction of costs through the saving of organic solvents and their recovery as well as in the positive environmental aspects. While the higher energy consumption for drying and the water sensitivity of various active materials represent a disadvantage of this process. Especially with nickel-rich and lithium-rich materials, there is a risk of Ni and Li being washed out.

Effort and producibility

The R&D expenditure to be carried out in the field of aqueous cathode production can be regarded as high. The adjustments to producibility are likely to be rather small.

Degree of maturity and market entry

The maturity can currently still be located in basic research. Aqueous binders are therefore still more of a research topic. However, if material-related problems (such as cathode powder or binders) are solved, a market launch could be possible from 2025. Thus, this approach can be classified as BNAT but is out of time scope of this study.

4.1.2.2. Anode

4.1.2.2.1. Graphite

Natural and synthetic graphite represent the status quo as anode material and has a specific capacity of approx. 360 mAh/g.

Aim and suitable cell formats

Until now, almost exclusively natural and synthetic graphite was used as anode materials for LIBs, and LTO was used for special applications. The further development of energy densities on the cathode side will in future also require new active materials on the anode side in order to enable meaningful electrode balancing. Another driver for the increasing substitution of graphite is the desired fast charging performance of future batteries.

The concrete aim is a further increase of the energy density, for example by increasing the density in the electrode layers or by using graphite-containing composites.

Bottlenecks and solutions

Graphites are used today as active materials in all cell formats and currently represent the state of the art, with no further massive improvements to the material or electrode to be expected. With regard to thickness optimization, graphite is already close to the theoretical limit. On the other hand, there is still development potential in the field of electrode development, e.g. by structuring the electrode or by mixing different types of graphite, conductive carbon black, conductive CNTs or similar.

Advantages and disadvantages

Overall, there are probably no other major advantages or disadvantages. It is an established system. With regard to increasing the energy density, however, graphite anodes are exhausted.

Effort and producibility

The expenditure of a further optimization is to be seen as a means, since there are hardly any optimization possibilities and further improvements are very complex. The producibility is given.

Maturity and market entry

Today, graphite products represent the state of the art and are available on the market.

4.1.2.2.2. Si/C composites

The transition from pure intercalation materials in LIBs to mixed systems with a low content of alloying materials such as silicon can represent a possibility to significantly increase the specific capacity of pure carbon anodes (372 mAh/g corresponding to LiC_6). Si offers a theoretical capacity of about 3578 mAh/g (corresponding to $\text{Li}_{15}\text{Si}_4$). Like graphite, the material has very good raw material availability and low toxicity. With a redox potential of less than 0.5 V against Li/Li^+ , a good compatibility to graphite-based anodes is given. Due to the high-volume change of Si in the alloy with Li of up to 300 %, electrodes with a high Si content are exposed to strong mechanical loads. Si/C composites can partially absorb this effect. With a mixture of 20 % Si and 80 % carbon, capacities of about 1000 mAh/g can be achieved.

Aim

Si composites with content of < 5 % Si are already being used commercially in High Energy-LIBs (HE-LIBs). Composites with a content of 20 % are currently in applied research (TRL 4-5) and could, in combination with NMC, enable a gravimetric or volumetric energy density of 300-350 Wh/kg and 1000 Wh/l in the future. From the point of view of performance, possible charge currents of 1 C - 3 C to 80 % SOC are predicted.

Bottlenecks and solutions

The change in volume leads to two types of degradation: The high mechanical load can lead to a reduced mechanical stability of the electrode and thus to the loss of the electrical contact of the particles. On the other hand, the volume change of the Si-particles causes a repeated breaking-up and rebuilding of the SEI (Solid-Electrolyte Interphase). The resulting loss of electrolyte and active material results in an irreversible loss of capacity.

Further optimization of the material and electrode architectures is necessary to cushion the volume expansion. Approaches exist in the nanoscaling of the Si particles or a porous and flexible structure of the composite structure. An important contribution to this is also seen in the further development of compatible binders. Porous C-structures can absorb about 10 % volume changes. With a volume change of 50-100 %, a strong influence on the service life is assumed with the current state of the art.

In order to increase the stability of the SEI during cyclisation, electrolyte improvements could contribute. Other approaches are seen in the production of coated Si particles, e.g. core/ shell structures. The lithium loss associated with the repeated build-up of the SEI could be compensated by a partial pre-lithiation of the anode.

Advantages and disadvantages

The main advantage of Si/C composites is the increase in both gravimetric and volumetric energy densities. As described above, a reduction in cell life seems inevitable.

Effort and producibility

The compatibility of existing electrode and cell production processes with Si/C materials is assessed as good. The suitability of the materials is seen in particular for cylindrical and prismatic cells, since in these formats a favourable external pressure can be applied to the electrode stack to mitigate expansion effects. Due to the easy aggregation of Nano-Si, strategies for the production of stable and processable dispersions have to be developed. At the material level there are currently various concepts for the production of complex structured composites with partly very good electrochemical properties. Scalability to industrial scale has yet to be proven in some cases.

There is a need to optimize materials at the level of applied research. The expenditure for the development of anodes with > 5 % Si content is regarded as low, for anodes with Si content >20 % considered to be high. The increase in the number of cycles is not considered mandatory. A certain reduction in cycle life appears acceptable if the capacity can be increased to the same extent through the use of Si/C composites.

Maturity and market entry

The technology is on the market. It is assumed that the share of Si will increase continuously. The further development path of the materials are pure Si anodes or anodes with a Si content of about 80 %. Thus, this approach can be classified as BAT or as BNAT, depending on the share of Si.

4.1.2.2.3. Lithium metal

In this approach anodes made of Li-metal are used instead of graphite or silicon. Conceptually, a very thin Li layer can be used. The Li of the anode is not necessary for the electrochemical reaction, since all the Li required is already present in the cathode material. The initial Li layer thus serves as a "starting point" for further Li intercalation during the charge of the cell.

Aim

Compared to other material concepts, metallic lithium is the anode with the highest specific capacity. The aim of this approach is to increase the energy density. For lithium-based materials, a cylindrical cell is best suited, as it best tolerates volume changes. The existing LMP technology, uses a prismatic cell design within a housing that controls volume changes cumulated on a bundle of cells through mechanical means. The order is here (as with Si/C-composites): Cylindrical is better than prismatic and this is better than pouch.

Bottlenecks and solutions

When using a lithium metal anode, there is a bottleneck in dealing with volume change and dendrite growth, especially at higher current densities. This leads to a structural loss of the anode, which on the one hand requires larger electrolyte volumes and on the other hand creates the risk of an internal short circuit if the dendrites penetrate the separator. Solution approaches consist in the use of solid electrolytes or appropriately added liquid electrolytes, which are intended to limit the loss of structure of the Li anode. Another bottleneck is that there are currently no commercial thin lithium foils available. In addition, contacting without carrier films is very difficult with regard to handling and further processing is also relatively difficult (reactivation of Li with air and water).

Advantages and disadvantages

The advantages of this approach are increased energy densities, but at the same time also disadvantages due to the change in volume and the associated effects on the service life.

Effort and producibility

The R&D expenditure for the implementation of the Li-metal anode is estimated to be high. New production concepts are needed to be able to produce the anode. This is because concepts for the processing of Li-metal anodes, such as their passivating coating to enable processing in the presence of oxygen or water in the atmosphere, are currently lacking. Cell design requires other techniques in order to cushion the volume expansion of the Li-metal anode.

Maturity and Market Entry

Lithium metal in the broad scale (with exception of the LMP technology) currently only works in the laboratory, but not in the product, and can therefore rather be classified as applied research. Li-metal anodes are not expected to enter the market before 2025. Thus, this approach can be classified as BNAT and may be out of time scope of this study.

4.1.2.3. Stable separator

The development of stable separators concerns separators that are thermally and mechanically stable in cell production and in field use. This applies in particular to so-called ceramic separators or ceramic-coated membranes.

Aim and suitable cell formats

The fundamental goal is to reduce the thickness of the separators while improving the safety of the cell as much as possible. Ceramic separators are currently 21-28 µm thick, ceramic-coated separators approx. 12-24 µm. The aim is to produce future thicknesses significantly thinner than 20 µm, but without safety losses, while simultaneously using high-energy electrodes. Currently, polyolefin membranes are coated with inorganic particles or separators are designed with a continuous layer of inorganic particles. No problems can be detected with the format if the inorganic particles are bonded well to the carrier and there is sufficient tensile strength for the winding/stacking process.

Bottlenecks and solutions

An essential bottleneck is the homogeneity of the coating and the processability of the separator. At the same time, the manufacturing processes must be presented in such a way that the costs of the separators can be developed in line with market requirements.

Advantages and disadvantages

In addition to higher thermal stability, a stable separator offers a high degree of safety (e.g. during nail test, overload test, hot box test). Another advantage is the increased cycle stability. The wetting and high-temperature processing of all-ceramic separators is also significantly better than with conventional membrane-based separators. The disadvantages are the increased costs compared to pure PP or PE. In addition, the ceramic materials are heavier. This means that ceramic-based or modified separators must be comparatively thinner than pure membrane separators in order not to impair the energy densities of the cells.

Effort and producibility

The cost of this approach for ceramic-coated separators is estimated to be low to medium, although small to medium adjustments may also be necessary for the producibility. The costs

for the ceramic separators can be classified as medium, as can the adjustments for producibility.

Maturity and market entry

Maturity is at least in the prototype stage, if not even ready for the market.

4.1.2.4. Electrolyte

4.1.2.4.1. Additives

The electrolyte has a significant influence on the life of the cell. State of the art are currently the LiPF₆-based electrolytes in carbonate solvents. These have electrochemical stability up to about 4.4 V. The stability window must be enlarged for the utilization of HV materials, e.g. up to 4.6 V for HE-NMC or 5 V for high-voltage spinels. Many of the difficulties currently encountered in the use of new active materials are due to instabilities in the electrode/electrolyte system. The development of suitable electrolytes can thus be regarded as a decisive "enabler" for all future HE systems.

Electrolyte additives are added to the electrolyte consisting of Li salts and carbonate solvents to improve its properties. For example, additives can improve the stability of the electrolyte or have a protective effect on the surface of active material particles.

Aim and suitable cell formats

The aim of additives is in particular to enable the use of new electrode materials or to increase the service life of such cells. Furthermore, properties such as non-combustibility, the window for operating temperatures (low-temperature electrolyte) or voltage stability can be improved. There are no limitations with the different formats, if the other cell components are adapted accordingly.

Bottlenecks and solutions

Difficulties exist in the search for suitable additives or additive combinations and in optimising their concentration in electrolytes. The lowest possible proportion is desirable in order not to impair the function of the electrolyte as an ion conductor.

Furthermore, cost restrictions apply to additives, which require the development of favourable manufacturing processes. The solution approaches exist in the area of basic research in the search for suitable compounds/materials and in the area of synthesis processes.

Advantages and disadvantages

With the additives suitable for Si anodes and HV cathodes, the advantages consist in enabling higher energy densities at cell level. In addition, lower costs for the silicon additives are to be expected. Compared to a component change, established main components (possibly cheaper or better suited for production processes) can be used.

On the other hand, the efficiency of the additives is a disadvantage in the case of silicon additives and HV additives. Either the additives have to produce a stable SEI or they repeatedly replicate SEI and are consumed in the process, reducing the energy efficiency of the cell. In addition, protective additives contribute nothing to the conductivity of the electrolyte and thus to the "function" of the battery, making them an additional passive element.

Effort and producibility

A distinction must be made between compatible additives for HV cathodes and Si anodes in terms of effort: For Si it can be regarded as low to medium, while for HV it is slightly higher

and is quantified as medium to high. Producibility seems possible in both cases, but requires minor process adjustments.

Maturity and market entry

In the case of additives for Si anodes and HV additives, one is in the research area or pre-prototype. A market entry could take place from the year 2020. Thus, this approach can be classified as BNAT.

4.1.2.4.2. Alternative liquid electrolytes

By changing the components of the electrolyte, it should become a non-flammable electrolyte, low-temperature electrolyte or electrolyte for high-voltage materials.

Aim and suitable cell formats

The aim of a component change is to increase the service life of the cell or to improve the application possibilities of LIBs. The exchange of salts or solvents aims, for example, to increase the usable voltage window (> 4.5 V) or to improve chemical stability, which is not available for many new active materials with standard electrolytes. Further goals are the reduction of flammability or the extension of the window for possible operating temperatures. When the components are changed, no problematics can be detected in the formats either, provided that the other cell components are adapted accordingly.

Bottlenecks and solutions

The concrete challenges are strongly dependent on the material/electrolyte system under consideration and depend on the exact objective of the electrolyte development. In HV applications, the oxidation stability must be guaranteed in relation to the active materials. When changing components, compatibility with the anode must also be ensured. Ionic liquids often have a too low conductivity, which limits the maximum current density (power rate). They are also relatively expensive.

Advantages and disadvantages

Enabling the use of HV materials could increase energy density at cell level. Non-combustible electrolytes also provide a higher degree of safety. With an extended operating temperature range, it may be possible to partially dispense with cooling if the stability of the SEI is still guaranteed. If the components are changed, the costs are to be considered disadvantageous.

Organic carbonates are relatively cheap, while all other materials are currently still quite expensive. In addition, the reduced cycle stability and service life of non-combustible electrolytes and low-temperature electrolytes represent a disadvantage.

Effort and producibility

When changing components, a distinction must be made between HV applications and the inhibition of flammability, as it is also the case with addition: The cost for flammability inhibiting electrolytes can be regarded as medium, while it is slightly higher for HV and is classified as medium to high. Producibility should be possible with minor adjustments.

Maturity and market entry

All in all, the approach of a component change in electrolytes is still very young and in the research stage, with the exception of non-flammability and low-temperature electrolyte. Market entry should therefore take place around the years 2025 to 2030. Thus, this approach can be classified as BNAT but is out of time scope of this study.

4.1.2.4.3. Polymer electrolyte SPE/CPE

Aim and suitable cell formats

Polymers can be made ion conductive by complexing with Li salts. The salts are dissolved in polymer chains. Ion transport takes place via the mobility of the chains in the polymer. The best known representative of this class is polyethylene oxide/LiTFSI. SPEs usually have a low ionic conductivity at room temperature, which prevents their practical application. Therefore, they need to be brought to a sufficient operating temperature that will ensure adequate conductivity for a given application (e.g., existing LMP technology operates at a minimum temperature of 60 to 80°C depending on the application). Conductivity of polymer electrolytes can be significantly increased by combining them with ceramic or metallo-organic nanoparticles to form composite electrolytes (CPE composite polymer electrolytes). Among other effects, the presence of nanoparticles inhibits the crystallization of polymer chains and thus increases their mobility.

In combination with a Li-metal anode and LFP cathode, the polymer-based LMP 100% solid batteries are already being used in commercial applications. Other polymer-based solid batteries are also used in test projects and those are considered at the TRL 7. LMP® cells of the current generation operating at 80°C reach performance levels of 240 Wh/kg, 360 Wh/l, 120 W/kg.

The raw material availability for the production of the polymer electrolyte is good. In battery systems, the costs are currently still determined by the Li anode, whose price increases inversely to the layer thickness. The importance of this technology for Europe is estimated to be high. It is assumed that value chains could be established within the EU. In this sense, the EU is regarded as internationally competitive.

Besides the described SPE/CPE, there are also solid polymer-ceramic hybrids and solid ceramic electrolytes (SCE) in development. Due to the reason, that for those technologies the market entry (for automotive applications) is not expected in the short-term, they are not described here in detail.

Bottlenecks and solutions

Weaknesses of the technology result from the low ionic conductivity and the resulting high operating temperature. Compared to SCEs the potential stability of polymer-based electrolytes is worse, so that use with high-voltage cathodes is currently only possible in exceptional cases. Solution approaches exist in the further search for suitable nano filler materials, other polymers or polymer combinations. The use of functional or protective layers can improve the chemical stability of the materials to each other. The R&D expenditure is estimated to be moderately high and lays in the area of material and production development.

Advantages and disadvantages

The main unique selling point of the SPEs/CPEs is the higher safety of cells and the possibility to better transfer the cell energy density to the module level by reducing passive components. By changing the components on the anode and separator/electrolyte sides, a higher volumetric energy density can be achieved. On the cathode side, there is no change compared to LIBs. In general, polymer electrolytes offer the possibility to carry out the preparation process dry or solvent reduced.

The overall high internal resistance of the solid batteries, which requires operation at high temperatures, is regarded as a disadvantage. However, in many of the world climates, very hot or cold, it can instead be an advantage over lithium-ion batteries (LIBs) that need to be

maintain around 25 °C for safety, performance and cycle life. In hot climates for example, the solid batteries will require minimal energy to maintain its operating temperature and moreover will not suffer from ambient at 40 °C or even 50 °C. In colder climate, the solid battery packaging that includes insulation to maintain internal operating temperature and efficient heating systems can also be an intrinsic advantage over LIBs that would also in this context require heating but cannot be overly insulated to enable cooling in warmer months.

Producibility

The producibility of SPE-based solid batteries is given and demonstrated by the latest market entry in 2011 in Europe of the LMP® technology. For production by other manufacturers, minor adjustments in the production technology from cell to module are necessary. Compared to SCE batteries, the flexibility of polymer layers makes them easier to process. There are no restrictions with regard to possible cell formats.

Applications

The use of the technology is seen in particular in applications with regular operation using moderate charge rates, in particular in extreme climates as this facilitates in hot environments or justifies in cold ones the permanent maintenance of the cells at their high operating temperature, part of which is obtained through the actual operation of the battery. Hence, possibilities exist in the area of stationary storage and fleet vehicles such as city buses or last-mile delivery trucks that operate during a portion of the day and are brought back to garages during off-hours.

Future development and vision

The aim of the development is to increase conductivity of the electrolyte to reduce the necessary operating temperature and maintain a uniform lithium deposition in spite of higher charging currents. To increase the energy density it is necessary to increase the voltage stability and decrease thicknesses of cell layers that do not contribute to the energy level, such as the separator and the cathode current collector. For example, in LMP technology, the current development is expected to increase the performance parameters to 250 Wh/kg, 400 Wh/l and 125 W/kg at 2000 cycles and a service life of 10 years by 2022.

Solid-battery technologies may be separated in two groups. The 100%-solid LMP technology first marketed in the early 2000s in North America and approximately a decade later in Europe is classified as a Best Available Technology (BAT) within this new approach of battery design. Other experimentally-proven solid battery technologies are in a second group that can be classified as BNAT.

Further technical improvements are conceivable through the use of so-called "single ion" conductive polymers. Sometimes these have a higher conductivity at a lower operating temperature than currently used systems. Due to the ion transfer number of 1 of such SPEs, the formation of Li dendrites could be prevented by the theoretically possible homogeneous Li transport and the avoided concentration gradients.

4.1.2.5. Cell design and cell formats

4.1.2.5.1. Optimization of inactive materials

In this approach, the current collector and the casing are understood as inactive materials. In addition, protective layers, binders, clamps, springs or pressure relief valves are also considered.

Aim and suitable cell formats

The aim of this approach is to increase energy density through inactive material optimization and material reduction (e.g. binder content). The approaches are very diverse. The reduction of layer and carrier thicknesses is often intended. The weight of inactive components can be reduced by substituting materials. The approach to optimize inactive materials is in principle independent of the format. The concrete strategies can, however, differ considerably, since there are strong requirements for cell design that are dependent on the structural shape (and also size).

Bottlenecks and solutions

Bottlenecks lies particularly in the processability with a reduction of the current conductor thickness or the casing-thickness. In addition, the warranty or proof of safety under the new modification represents a bottleneck.

Advantages and disadvantages

One advantage of optimizing inactive materials is weight savings and space optimization. In addition, the material savings can result in cost advantages. The switch from steel to aluminium, for example, can result in corresponding cost disadvantages due to higher material prices. In some cases, however, this is already state of the art, especially for prismatic cells.

Effort and producibility

The expenditure is to be estimated rather as low to medium. For example when using an aluminium case instead of steel. The producibility can also be achieved by a low to medium effort in the adaptation.

Maturity and market entry

The degree of maturity is generally well advanced and can be located in the area of prototypes/demonstrators to market maturity. Accordingly, some approaches are already on the market. Thus, this approach can be classified as BAT up to BNAT.

4.1.2.5.2. Stacking instead of winding

In the area of the entire cell (prismatic and pouch), the transition from winding the cell to stacking the individual electrode packages represents a considerable opportunity to increase the energy density due to a higher degree of cell filling. There are two different procedures for inserting the electrode packs into the cell housing: Winding the electrode packs and stacking. Winding is currently still predominantly used for prismatic and cylindrical cells, while pouch cells are predominantly stacked. During winding, the coated anode and cathode films are wound separately by the separator, while during stacking (e.g. Z-stacking) individual cathode and anode sheets are inserted laterally into the separator.

Aim and suitable cell formats

The aim of stacking is to increase the filling level by reducing the dead volume in the cell housing. The filling level is comparatively lower during winding, e.g. due to the resulting radii. The stacking process is particularly suitable for prismatic cell formats and also for pouch cells.

Bottlenecks and solutions

The bottleneck, however, is the cycle time for stacking. Since this is a pick-and-place process, it takes somewhat longer. In addition, the stacking process can be differentiated according to the individual processes (e.g. stacking single sheets, Z-folding, etc.), in which the cycle times

vary again. Irrespective of the type of stacking process, however, the cycle times and the higher costs for the pick-and-place process represent the central challenges.

Advantages and disadvantages

It is possible to increase the filling degree and thus the energy density by stacking instead of flat winding in prismatic cells. In addition, a better pressure distribution in the cell and, if necessary, easier processing of thicker layers will be achieved due to the higher filling degree, since no more small bending radii are produced. The mechanical stress at the edges is also lower during stacking, which can have a positive effect on the service life of the cell. The disadvantage of the stacking process, on the other hand, is the larger number of cut edges, but otherwise there are rather no disadvantages compared to wound cells.

Effort and producibility

The R&D effort to address these problems can be seen as a means. Producibility still requires medium adjustments.

Maturity and market entry

The stacking process has already been industrialized and the market entry has already taken place. Thus, this approach can at least be classified as BAT.

4.1.2.6. Battery management system (BMS)

4.1.2.6.1. Electricity meter with 2-3 physical measuring ranges

The task of the Battery Management System (BMS) is the intelligent and optimised operation of the battery, which optimises the service life, reliability, safety and economy of the battery system. For this reason, various sensors for temperature, voltage and current measurement are integrated in the individual battery modules. On this basis, four R&D challenges are of particular relevance for the BMS: A total current measurement with 2-3 different physical measurement ranges, sensorless temperature determination of all battery cells, the marriage of specifications for electronics for automotive and stationary applications and online electrochemical impedance spectroscopy. While the first three approaches aim at an optimized recording of the current battery properties, the approach for the development of electronics for automotive and stationary applications rather includes a life-cycle focus and a more economical second use of the system (also the other two approaches may also play a role therefore)⁷.

Aim and suitable cell formats

In today's battery systems, electricity meters are usually only able to cover one physical measuring range.

By using electricity meters with 2-3 physical measuring ranges, the currents can be measured more accurately and the SOC of a battery can also be determined more accurately. This allows a better utilization of the capacity and a simultaneous reduction of battery ageing.

⁷ The role of the BMS for 2nd life applications will be further explained in chapter 4.2.4.2 Second-life applications

Bottlenecks and solutions

There are no bottlenecks worth mentioning. Only the effort concerning the hardware integration increases a bit and has to be implemented as cost-optimal as possible. In addition, the costs of the electronics for the electricity meter must be taken into account.

Advantages and disadvantages

If the slightly increased costs for electronics are accepted or reduced, electricity meters with 2-3 physical measuring ranges allow a more accurate estimation of the condition of the battery and especially of the SOC and thus increase the usable capacity and reduce battery aging.

Effort and producibility

The R&D expenditure for this approach is rather low and producibility is largely given.

Maturity and market entry

The degree of maturity can therefore be seen in the area of the prototype/demonstrator. Electricity meters with 2-3 physical measuring ranges are already partly used today. A broad market entry could then take place from 2020. Thus, this approach can be classified as BNAT.

4.1.2.6.2. Sensorless temperature measurement

Until now, measuring the temperature of the cells required complex wiring and the direct physical connection of a temperature sensor to the cells. A new alternative approach therefore pursues temperature determination without direct use of a temperature sensor e.g. via intercept frequency.

Aim and suitable cell formats

The aim of sensorless temperature determination is to determine the condition of a single cell more precisely. This increases the number of measured cell temperatures, which in turn makes it possible to better monitor the battery system in order to detect abnormal behaviour in the event of an error of a single cell at an early stage and to prevent a possible thermal runaway. On the other hand, the approach does not require any additional wiring. Sensorless temperature determination is suitable for all formats, but less relevant for cylindrical battery systems with many small cells connected in parallel, since the large number of cells makes it difficult to determine which cell temperature ultimately deviates.

Bottlenecks and solutions

There are still big problems because of the noisy environment (e.g. because of the motor converter). The disturbances have to be filtered out and the handling of differently aged cells with different internal resistances is a challenge.

Advantages and disadvantages

Despite these bottlenecks, the advantages of sensorless temperature measurement are high. With regard to battery safety, the indirect determination of the temperature of each individual cell via its voltage and behaviour represents a significant added value. Sensorless temperature determination could also act as an early warning in the event of faults. The disadvantages of such an application are small. There are minor additional costs in electronics as more components are required.

Effort and producibility

The R&D expenditure for sensorless temperature determination can be regarded as medium. Producibility, on the other hand, is given.

Maturity and market entry

The maturity level of this approach is currently still in the field of basic research. Market entry is therefore only likely to take place in the medium term between 2020 and 2025. Thus, it can be classified as BNAT.

4.1.2.6.3. Compatibility of electronics for automotive and stationary applications

The design of electronics in today's battery systems is strongly application-oriented. Accordingly, it can only be used for one application at a time. Which then would be a barrier to ecodesign requirements when products are not designed for both ESS and EVs. The design of the electronics for both automotive and stationary use would make it possible to operate the battery after its use in the automobile also in the stationary area, without having to accept major compromises with regard to the required performance. Therefore, on the one hand, automotive requirements would have to be met. On the other hand, requirements for the stationary sector such as a service life of 20 years and operation 24 hours a day, 7 days a week. The type of cell formats does not play a role in this approach.

Aim and suitable cell formats

The aim of this approach is therefore to use electronics that are suitable both for automotive applications and for subsequent stationary applications. Although there are OEMs who also use their automotive batteries for stationary applications, the batteries are not designed or optimized for this purpose.

Bottlenecks and solutions

As a central bottleneck, the additional costs arising from the fact that different requirements are placed on the electronics can be mentioned here. These, however, are to be regarded as low.

Advantages and disadvantages

The resulting advantage from the compatibility of electronics for automotive and stationary applications can be classified as a means, provided that Second-Life as an application will also be relevant in the future. The potentially high costs for second life applications can be seen as a disadvantage. How decisive these are, however, ultimately depends on the respective Second Life business model.

Effort and producibility

The expenditure is rather small. The producibility is also given.

Degree of maturity and market entry

The approach is still more in the area of basic research. The time of market entry is strongly dependent on the development of business models based on 2nd life concepts. The approach should therefore reach market maturity between 2020 and 2025 at the earliest. Thus, it can be classified as BNAT.

4.1.2.7. Thermal management

4.1.2.7.1. Improved battery temperature control during fast charging

The overriding goal at system level is to make the best possible use of existing capacity (or optimise usable capacity) and to minimise overhead in terms of weight and volume. The

central problem here is thermal management, which not only leads to different aging but also to derating of the electrical properties, resulting in lower system performance.

The R&D challenges in the field of thermal management concern rapid charging with simultaneous optimization of the service life and homogenization of the temperature in the battery system over the operating time. The focus of the objectives in the area of thermal management is therefore on increasing or maintaining the service life, especially if the battery is quickly charged and thus high currents and temperatures are generated in the battery system.

During fast charging (up to 350 kW in the future), stronger continuous currents flow through the battery system for several minutes than during driving (more likely 20-40 kW) and lead to a high thermal load. Temperature control of the cells is therefore necessary and will have a considerable effect on the service life of the battery system.

Aim and suitable cell formats

The aim of a suitable temperature control is to limit the reduction in service life and to avoid derating even under the extreme thermal stresses of fast charging. In principle, the format of the cells is irrelevant. All formats can be fast charged. However, the format sometimes has a strong influence on the current carrying capacity of the cell contacts and on the quality of the thermal resistance. For example the cell contacts of a pouch cell are comparatively thin, which leads to a higher resistance and thermal load during charging.

Bottlenecks and solutions

The higher costs for the thermal management and the charging stations as well as the definition of standards for the charging stations are to be seen as an essential bottleneck.

Advantages and disadvantages

The advantage that would result, however, would be faster charging without a drastic reduction in service life. In return, however, the high costs of creating the infrastructure must be taken into account.

Effort and producibility

The R&D effort to be undertaken in relation to fast charging is estimated to be high to very high, especially when the system needs to be cooled, for example at rest areas where the charging stations are frequently used. The cost of producibility is also very high and requires new production concepts.

Maturity and market entry

At present, fast charging as defined above (up to 350 kW), in vehicles (excluding buses) can still be seen in the stage of basic research (also the Tesla Supercharger v3 will be able to charge with 250 kW peak). However, market entry could be expected from 2020. Thus, this approach can be classified as BNAT.

4.1.2.7.2. Homogenization of temperature

The cells in a battery system may have different temperature levels during operation. This primarily depends on how the cells are connected and loaded. Depending on the temperature level, their performance changes at different speeds. Each cell has its own temperature distribution. However, homogenization ensures that this temperature distribution is identical for all cells and that the ageing of each cell progresses at the same rate.

Aim and suitable cell formats

This homogenization leads to an even ageing of the cells. Through the battery system, this reduces the need for cell derating and increases both uptime and life. In addition, the internal cell resistances and thus the equal cell aging, have a positive effect on the fast charging performance. The homogenization of the temperature is rather independent of the cell format and can therefore be applied to all formats, but with different effort.

Bottlenecks and solutions

There are currently no larger bottlenecks.

Advantages and disadvantages

If the homogenization of the temperature is successful, the advantage is very high, since a more even cell aging is achieved. The internal resistance of the cells thus also changes uniformly in all cells and with it also the power consumption capacity of the cells. This means that the balancing effort can be reduced, as the cells only drift further apart to a limited extent than has already been the case in production. These advantages are at the expense of slightly higher material costs, whereby the absolute amount cannot yet be conclusively quantified. In addition, there is a higher expenditure in the cooling system.

Effort and producibility

There is still room for improvements to a certain extent, but at the same time it requires some extensive changes (e.g. direct cooling of cells), although the effort involved is rather small. Producibility is given.

Degree of maturity and market entry

In terms of maturity, the approach is in the field of applied research or prototype/demonstrator. There are already some commercial applications. For example, Tesla currently already has a liquid cooling system with which 1C charging is possible. However, it is still controversial whether this will affect the service life. The overriding aim of this challenge is therefore to achieve uniform cooling of the cells without reducing the service life. This could be achieved by the year 2020. This approach can thus be classified as BNAT.

4.1.2.8. Housing and additional components

4.1.2.8.1. Use of new materials

The housing of the battery system encloses and protects the internal components of the battery system, as well as the outside of the vehicle. R&D challenges in this area include the use of new materials to make the case lighter or smaller in volume, and the design and material optimization of the battery junction box to achieve the same goal. The use of new materials for or within the housing, covers a wide range of possible materials such as mica, supra thermal insulators, lightweight materials or phase change materials for thermal insulation.

Aim and suitable cell formats

The aim of using these new materials is to reduce both weight and volume overhead, regardless of the material. Finally, such a reduction makes it possible to increase e.g. the range of the vehicle.

Bottlenecks and solutions

There are currently no serious bottlenecks visible. However, a large number of tests are still necessary before a market launch in order to investigate and demonstrate the advantages of the materials, depending on the type of cell and application.

Advantages and disadvantages

The resulting advantages can be considered medium to high, as the materials have a positive influence on weight and ageing. The only disadvantage could be low additional costs.

Effort and producibility

The effort required for material development depends on the specific case. However, it can tend to be classified as high to very high. New production concepts may also have to be developed in some cases in order to achieve producibility.

Maturity level and market entry

Most of the materials mentioned are currently still in the pre-development stage. Nevertheless, some materials are already on the market, so that the market launch of individual materials has already taken place. This approach can therefore be classified as BAT and BNAT depending on the considered material.

4.1.2.8.2. Change in system voltage (48V, 800V)

A further R&D challenge at system level is to design the battery voltage of a BEV to 800V instead of common 400V. This increase in voltage is intended to noticeably improve the performance of the battery system in terms of power consumption and output. Alternatively, a trend towards lower system voltages, i.e. 48V, is currently being observed.

Aim and suitable cell formats

The aim of the voltage increase is to increase the performance of the battery system. The approach is suitable for all cell formats. The voltage reduction to 48 V aims at a cost reduction of the battery periphery and the BMS.

Bottlenecks and solutions

The bottleneck to series production readiness of 800V systems is the guarantee of safety, since some of the components have yet to be developed and their safety must be proven accordingly. Power electronics for 48V systems are available in principle, but challenges still have to be solved by the higher currents.

Advantages and disadvantages

The advantage of using 800V systems lays in the increased performance of the battery system through more power and braking force, which is particularly relevant for applications in the high-performance and premium automotive segments. The disadvantage resulting from this measure is the increased costs. In terms of maturity, is the 800 V system developed in parallel with the 400V or 600V system.

The main advantage of 48V systems is the lower cost of automotive electronics and powertrain. However, significant disadvantages result from the high currents, which tend to have a negative effect on the power efficiency of the overall system and generate higher power transmission costs.

Effort and producibility

The R&D expenditure to be carried out for 800V systems can be classified as very high. It is expected that medium adjustments will be necessary for producibility.

48 V drives differ fundamentally from 400V or 600V systems. It is assumed that 48V systems will not be used in previous xEV models. The R&D expenditure is estimated to be moderately high.

Maturity and market entry

To date, the first 800V prototypes are already available, but no series production has yet been reached, which means that the maturity is in the prototype/demonstrator range. It should be possible to reach market maturity in the short term. Battery systems with a higher voltage of 800 V should enter the market by 2020. The use of 48 V systems is seen in particular for industrial applications (transport, industrial trucks) and for small vehicles (scooters, small xEV in particular PHEV). First prototypes and small series are already available. The approach can therefore be seen as BAT (48V) and BNAT (800V).

4.1.2.8.3. Optimization of the battery junction box and new solutions for contactors

The battery junction box (BJB) contains electrical-mechanical components such as BMS or contactors and relays. Their design and material optimisation (e.g. all-solid-state relays) is the focus of this approach.

Goal and suitable cell formats

The aim of optimizing the BJB is to reduce weight and volume, but also costs. The approach is suitable for all formats and independent of cell size or cell format.

Bottlenecks and solutions

The bottleneck, which has to be solved here, lies in the guarantee of safety. For example, in the case of a mechanical contact, it is easy to ensure that it is open, as opposed to a semiconductor switch.

Advantages and disadvantages

The solution of the bottleneck is opposed by a large cost saving for the components of the BJB as well as a reduction of the volume and weight of the BJB with no recognizable disadvantages.

Effort and producibility

However, the effort required to solve this bottleneck is high. New production concepts are likely to be necessary.

Maturity and market entry

Research in this area is between basic research and applied research. Market entry could take place in the medium term between 2020 and 2025. So far, the bottleneck on the subject of security still stands in the way of the breakthrough. Thus, this approach can be classified as BNAT.

4.1.3. Overview of the improvement design options and classification regarding BAT and BNAT and expected timeline

Based on the previous section the following BAT and BNAT is identified including a timeline for which it can be expected to enter the market, see Table 2.

Table 2: Expected timeline for the market entry of the improvement options

		Today (BAT)	2020 (BNAT)	Until 2025 (BNAT)	From 2025 (out of time scope)
Cathode	Nickel-rich materials				
	High-energy NMCs				
	High-voltage spinels				
	Layer thickness				
	Aqueous cathode production				
Anode	Graphite				
	Si/C composites				
	Lithium metal				
Electrolyte	Additives				
	Alternative liquid electrolytes				
	Polymer electrolyte SPE/CPE				
Separator	Stable separators				
Cell design and cell formats	Stacking instead of winding				
	Optimization of inactive materials				
Battery management system (BMS)	Electricity meter with 2-3 physical measuring ranges				
	Sensorless temperature measurement				
	Compatibility of electronics for automotive and stationary				
Thermal management	Improved battery temperature control during fast charging (-> 350 kW)				
	Homogenization of temperature				
Housing and additional components	Use of new materials				
	Change in system voltage (48V, 800V)	48V	800V		
	Optimization of battery junction box/ new solutions for contactors				

Following the description given before, a BAT Case (considered on component level) may contain some or all of the following improvement options as listed in Table 2 for "Today".

- Higher share of Ni (in case of NMC but not already NMC 811 Ni-rich).
- Additives to the graphite anode
- Increased layer thickness compared to previous versions of the cells.
- Thickness of the separator is further reduced-
- Reduction of inactive materials such as binders, or reduction of current collectors' thickness.
- Isolation, Insulation and weight reduction of housing.

A BAT may include all or most of these options depending on the intended application. As BNAT can be considered those technologies and improvement options that have not entered the market yet but might be available until the year 2025. Table 2 depicts the following improvement options:

- On side of the cathode this will be the Ni-rich materials (NMC811) but also the High voltage spinels and High energy NMC might be an option.
- For the anode, it can be expected that, even there will still be pure graphite anodes, the anode will be composed with a certain share of Si.
- Additives in the electrolyte will be an issue, probably together with alternative and polymer electrolytes as described before.
- The separator will be further improved regarding safety and thickness.
- Regarding the cell design it can be expected that the reduction of inactive materials will be further proceeded, while for the prismatic cell format also the stacking process might become more and more common.
- The BMS and sensing of the cells might be improved by measuring more than one physical range to improve the cell management and increase the service life of the battery system. Also a sensorless measurement is thinkable, which would reduce the wiring and therefore improve the energy density and reduce the costs (materials and production). Furthermore, when considering second life application, it might be an option to use electronics suitable for both, automotive and stationary applications.
- Another step regarding improving the service life is to improve the thermal management to homogenize the cell temperature and thus to increase the whole battery systems service life. It has also to be considered that fast charging-capability will play a more prominent role in the future. The thermal management has therefore to be able to deal with the high currents going along with that.
- Finally, the whole housing will be further improved (as on cell level) by eliminating inactive materials or by using new materials offering a higher value regarding safety, weight or costs. This will especially address the junction box and contactors. Additionally, the whole battery system may be adapted to new system voltages as e.g. 48V or even 800V.

Since the added value of an improvement option strongly depends on the intended application, a BNAT may include one or more of these options depending on the application.

4.2. Subtask 4.2 - Production, distribution and end-of-life

4.2.1. Product weight and Bill-of-Material (BOM)

Based on the insights of Task 2 and Task 3 the following applications can be identified as a potential baseline to build the base cases⁸.

Table 3: Key parameters of market products used to build the Base case

Application Parameters	Passenger car BEV large (80 kWh)	Passenger car BEV small (40 kWh)	Passenger car PHEV	Truck BEV (40 t)	Truck PHEV(40 t)	Residential Storage	Grid stabilisation Storage
Economic lifetime of application [year]	13	14	13	14	12	20	20
Typical capacity of the application	80	40	12	360	160	10	30 000
Nominal battery system capacity [kWh]	80	40	12	30	20	10	10
Number of cycles per year	120	120	120	300	600	250	250
Maximum calendar lifetime of the installed battery (no cycling ageing)	20	20	20	20	20	25	25
Maximum number of cycles for battery system until EoL (no calendar ageing)	1500	1500	2000	2000	3000	8000	10 000
SoH @ EoL of battery system relative to declared capacity	70%-80%	70%-80%	60%-80%	70-80%	60-80%	50-70%	60-70%

For the base case definition, we are looking at the different applications to define the system capacity and the system designs. The battery systems of the applications are thereby using different cell chemistries as already described in task 3. Therefore, on cell level typical battery cells on the market are used as a database for the BOM. But due to the high heterogeneity of products on the market it is not possible to identify a reliable base case for the applications, since they wouldn't be representative in terms of cell chemistry or cell format. To come to a base case which can be seen as representative for the products on the market and therefore could be considered as a base case, a virtual battery system for each of the above-mentioned

⁸ The corresponding values listed below should not be considered as an exact value but rather as a typical example for the application. For sake of transparency, the values are therefore not given in a range but listed, as they will be used for the calculations in task 5.

applications is build. The different share of cell chemistries in the product thereby reflects its market share within the specific application.

Therefore, the following distribution of cell chemistries is estimated, based on the results of Task 3 and, where no reliable information could be gained, on own estimations.

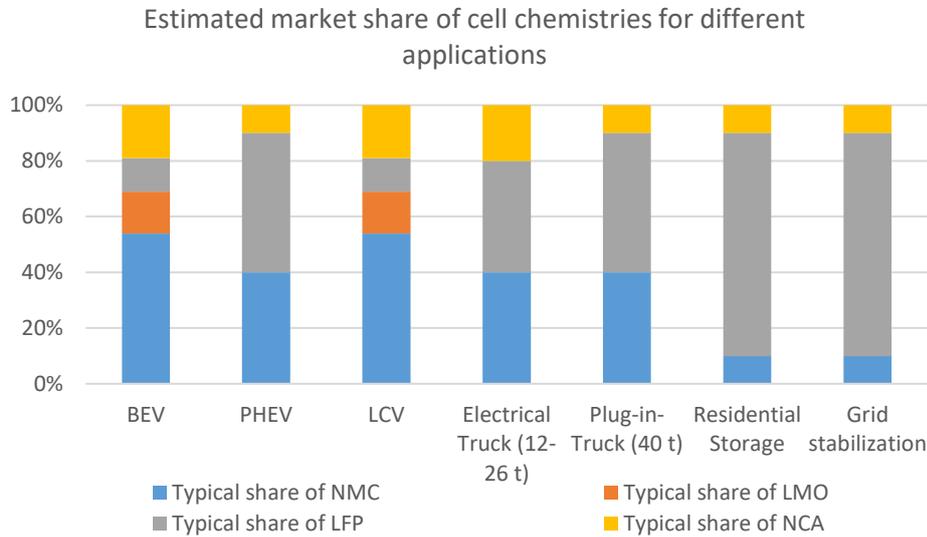


Figure 6: Distribution of cell chemistries within the different Base Cases (based on Pillot 2017; Hill et al. 2018 and own assumptions)

However, the BOM for the cells within the base cases is based on common cells on the market. To reflect a typical product for the different applications by the mixture of those cells, the cells were chosen to cover the most common cell chemistries and also the most common cell formats as described in the previous chapters. The following table depicts the considered cells as well as their corresponding BOM.

Table 4: Specifications and BOM of the considered cells as database for calculating the base cases (mainly based on information from Takeshita et al. 2016, 2018)

		NMC Pouch cell (form GREET Model)	LGC Volt (Gen2)	SDI BMW i3	Panasonic 18650	BYD 200Ah for e6/k9
General Information	Format	Pouch	Pouch	Prismatic	Cylindrical	Prismatic
	Chem.	NCM 622	NCM424/NCM111	NCM523/NCA(80/10/10)	NCA (82/15/3)	LFP
	Ah	59	25.9	60	3.18	200
	Wh	212	96	222	11.45	640
	V	3.6	3.7	3.7	3.6	3.2
	Wh/kg	218	173	122	48.5	108
	W/mm		171	173	18.25	410
H/mm		233	125	65.1	146	
T/mm		7.5	45	18.25	58	

		Material	g/Wh	g/Wh	g/Wh	g/Wh	g/Wh	
BOM Cell level	Kathode	Cathode active material	1.488	2.091	2.486	1.438	2.188	
		Cathode active material 1	Fe	0.000	0.000	0.000	0.000	0.774
		Cathode active material 2	Co	0.169	0.230	0.100	0.123	0.000
		Cathode active material 3	Ni	0.505	0.381	0.337	0.655	0.000
		Cathode active material 4	Mn	0.157	0.539	1.006	0.000	0.000
		Cathode active material 5	Al	0.000	0.000	0.005	0.019	0.000
		Cathode active material 6	Li	0.199	0.251	0.189	0.194	0.096
		Cathode active material 7	P	0.000	0.000	0.000	0.000	0.429
		Cathode active material 8	O	0.459	0.688	0.849	0.447	0.887
		Cathode conductor	Carbon	0.100	0.110	0.114	0.019	0.313
		Cathode binder	PVDF	0.134	0.099	0.106	0.013	0.104
		Cathode additives	ZrO2	0.000	0.000	0.000	0.000	0.000
		Cathode collector	Al foil	0.384	0.304	0.303	0.141	0.461
	Total cathode		2.107	2.602	3.008	1.611	3.065	
	Anode	Anode active material	Graphite	0.966	1.104	1.101	1.017	1.563
		Anode binder 1	SBR	0.000	0.046	0.030	0.017	0.041
		Anode binder 2	CMC	0.000	0.000	0.030	0.017	0.041
		Anode collector	Cu foil	0.738	0.554	0.732	0.355	1.001
		Anode heatresistnt layer	Al	0.000	0.000	0.190	0.000	0.000
		Total anode		1.705	1.704	2.082	1.404	2.646
Electrolyte	Formulated electrolyte		0.005	0.801	1.410	0.410	1.719	
	Fluid	LiPF6	0.103	0.103	0.181	0.053	0.220	
	Fluid	LiFSI	0.000	0.000	0.000	0.000	0.000	
	Solvents	EC	0.289	0.256	0.451	0.131	0.550	
	Solvents	DMC	0.289	0.256	0.451	0.131	0.550	
	Solvents	EMC	0.000	0.184	0.324	0.094	0.395	
	Solvents	PC	0.000	0.000	0.000	0.000	0.000	
	Total electrolyte		0.681	0.799	1.408	0.410	1.715	
Separator	Separator	PE 10 micron+A	0.016	0.000	0.000	0.000	0.000	
	Separator	PP 15 micron +	0.071	0.187	0.000	0.000	0.000	
	Separator	PP/PE/PP	0.000	0.000	0.279	0.000	0.336	
	Separator	PE-Al2O3	0.000	0.000	0.000	0.092	0.000	
	Total separator		0.087	0.187	0.279	0.092	0.336	
Cell Packagin	Tab with film	Al Tab	0.000	0.052	0.000	0.000	0.000	
		Ni Tab	0.000	0.167	0.000	0.000	0.000	
	Exterior covering	PET/Ny/Al/PP/	0.014	0.200	0.000	0.000	0.000	
	Collector parts	Al leads	0.000	0.000	0.017	0.000	0.023	
	Collector parts	Cu leads	0.000	0.000	0.047	0.000	0.070	
	Collector parts	Plastic fasteners	0.000	0.000	0.072	0.000	0.031	
	Cover	Valve, rivet term	0.000	0.000	0.505	0.162	0.156	
	Case	Al	0.000	0.000	0.678	0.000	1.250	
	Case	Ni plating Iron	0.000	0.000	0.000	0.518	0.000	
	Total cell packaging		0.014	0.419	1.318	0.680	1.531	

While the database for determining the BOM on cell level can be considered as appropriate, it becomes quite challenging on the module or system level, since there are manifold design options differing from OEM to OEM and by application. BOM for those levels can hardly be found and if so, because of their low number or the date of release, they could hardly be seen as a base case in terms of a representative product. However, different literature sources were reviewed, mostly in the context of LCA studies to gain information about the BOM on module and system level (Ellingsen et al. 2014; Kim et al. 2016; Majeau-Bettez et al. 2011a; Yuan et al. 2017; Cusenza et al. 2019).

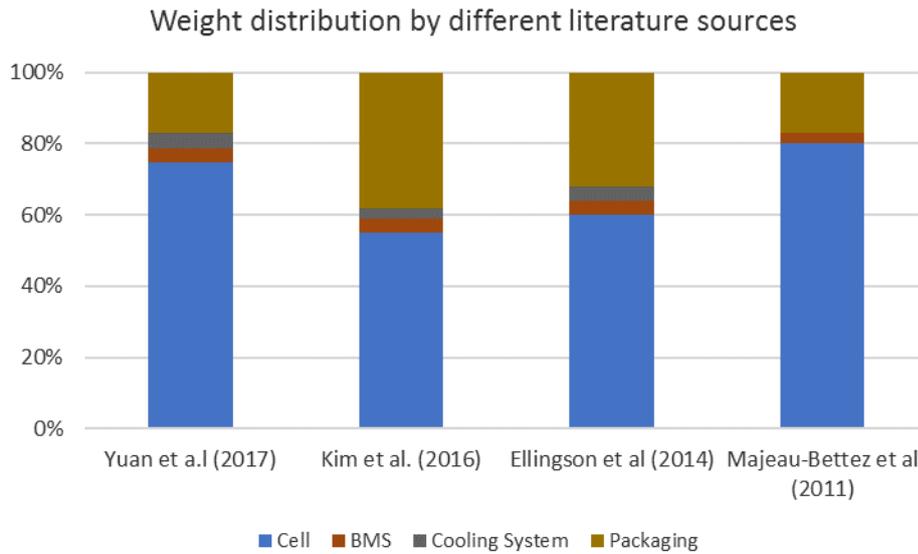


Figure 7: Weight distributions given in literature

Considering the weight distributions given in literature for different battery systems, shows that the weight of the cells (incl. cell housing) has the highest share in total battery system weight. It furthermore visualizes, that the BMS and Cooling system typically has a weight of 3-5%. Anyhow, regarding the share of the packaging varying opinions exist. A part of the explanation for the comparatively high share of packaging in the case of Ellingson might be that the system is intended for a PHEV application wherefore a lower number of cells is needed and thus the share of the packaging is relatively increased. For Kim et al. the reason may lay in the high number of 430 low-capacity cells, which have to be packed into modules and thus the high corresponding volume needed to be covered by the system housing. For a better interpretation of the value in the previous table, the following Table 5 gives an overview of the key parameters for the battery systems used in the reviewed studies:

Table 5: Overview of the key parameters for battery systems used in reviewed studies

	Yuan et al. (2017) LMO	Kim et al. (2016) LMO/NMC	Ellingson et al. (2014) NMC
Capacity	24	24	26.6
Cells	192	430	360
Total weight	167	303	253
Nom. voltage	3.85	3.7	3.65
Cell Ah	32	15	20

It becomes obvious, that the cell capacity of the battery cells is quite low compared to today, This again leads to a higher number of cells in the modules by a comparatively low system capacity. Since today's system capacities are higher, information about the weight distribution of today's state-of-the-art battery systems can hardly be transferred from these studies. For this reason some own analyses were conducted by using the BatPaC-model (Nelson et al. 2017). The modelling was conducted with the aim to receive information about the sensitivity of the weight distributions depending on the cell chemistry (NM333, NMC 622, LFP and LMO), the system size (40 kWh and 80 kWh) and the application (PHEV or BEV). The modelling results are depicted below.

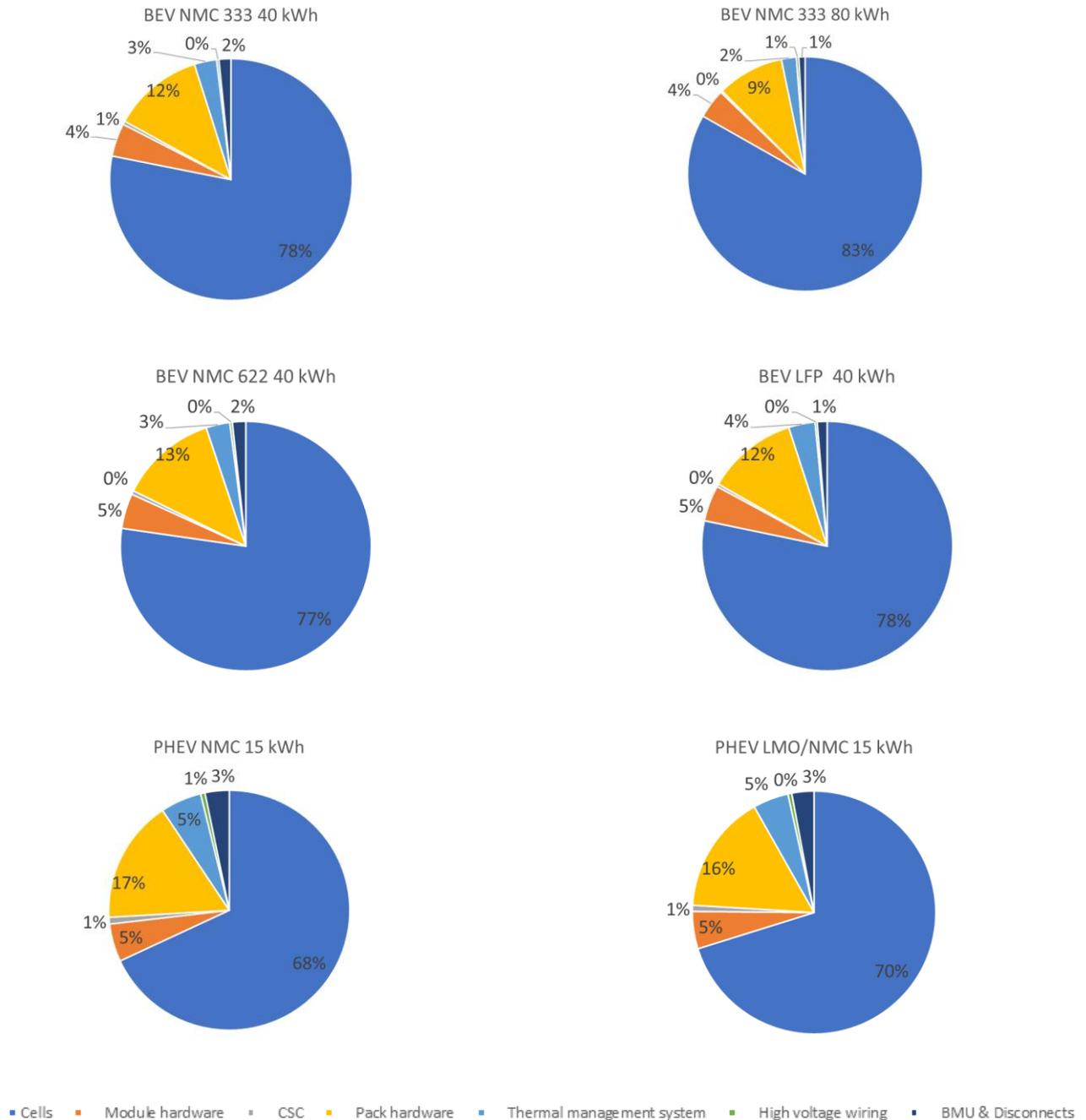


Figure 8: Analyse of the weight distributions by different system capacities, cell chemistries and applications (own analyse based on Nelson et al. 2017)

The modelling results on the one hand stress out, that the share of the BMS and thermal management also is approximately 4-5 % of the total battery system weight (as also indicated by the literature review). On the other hand they depict that, as already expected, the share of cell weight is comparatively lower for PHEV applications than for BEV. However, also an influence depending on the system capacity becomes visible, while a significant difference regarding the cell chemistry cannot be observed. A major take away is thus, that the module (also the cell format stays the same) has an equal share of ~5%. The share of the packaging therefore differs slightly for BEV and PHEV, due to the previously described relation between cells and packaging volume. Thus considering the results of the literature review (Figure 7)

and the modelling (Figure 8), the following weight distributions as shown in Figure 9 are estimated for the different applications (also no further differentiation is made between BEV for Passenger car LCV or Truck, PHEV for passenger and Truck or residential and grid stabilization application).

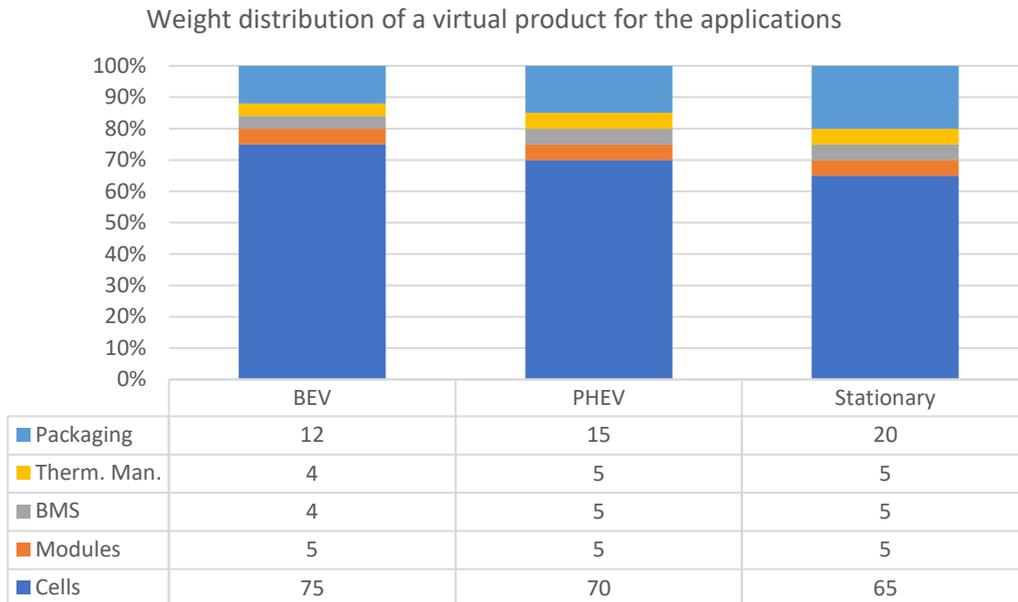


Figure 9: Weight distribution of a virtual product for the applications (own assumptions based on Figure 7 and Figure 8)

After defining the weight distributions on different levels for the applications, the concrete share of materials has to be determined. Here again, the heterogeneity of products and the availability of reliable up-to-date data is not given. Based on available in-house information the following estimations are made for the share of different materials in the module. Thereby a differentiation according to the cell formats has to be considered. For the modules, the material compositions as depicted in Figure 10 were assumed for a virtual product on the market.

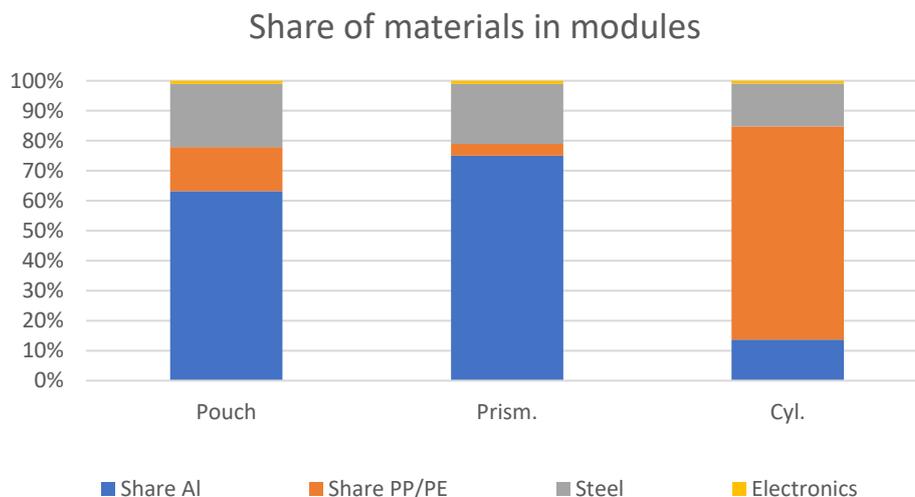


Figure 10: Share of materials in modules due to different cell formats (own assumptions based on internal data)

Regarding the material composition a relatively high share of Al is estimated in case of the pouch or prismatic format as e.g. for the casing or cooling plates. Also steel plays a prominent role, since it is also used as an alternative to Al-casings or e.g. for the tightening of pouch cells. Furthermore, the share of plastics is considered comparatively high for the cylindrical cells especially because of the cell brackets. Furthermore, often parts of the module as e.g. the lids are made of plastics. The share of plastic is also considered higher for pouch cells than for prismatic cells due to the reason that they have to be put into frames to provide them the necessary stiffness.

Finally, also the share of materials for the packaging has to be defined and is depicted in Figure 11. Here it is assumed that no significant difference regarding the relative share of materials is made between BEV and PHEV applications. The assumptions are based on the previously described sources. However, since for stationary applications, the weight is not seen as critical as for mobile applications, a higher share of steel is assumed.

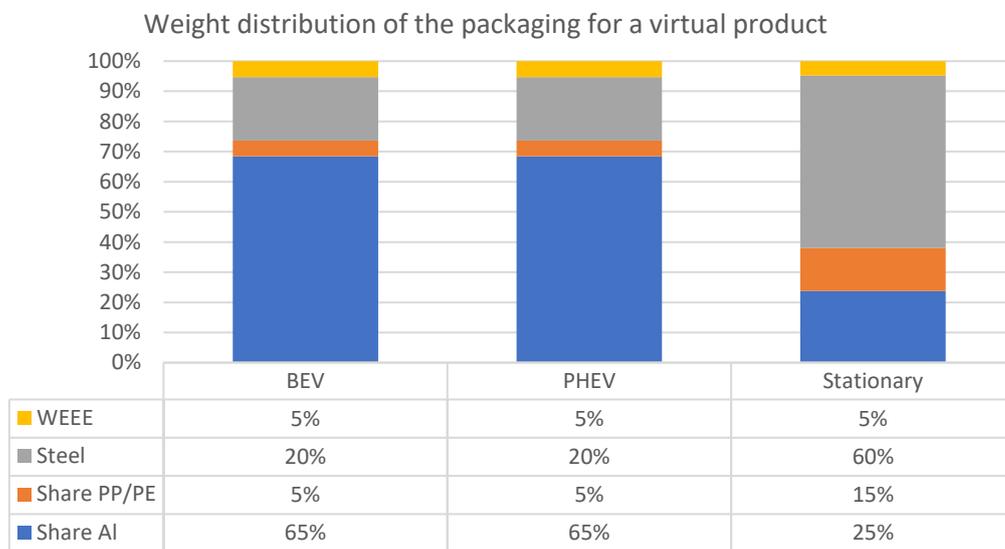


Figure 11: Weight distribution of the packaging for a virtual product⁹

Based on the described data and assumptions, the BOM for the different applications was calculated based on the BOM from Table 4 and information from Figure 9 to Figure 11. The resulting BOM for the different applications is displayed in the following Table 6.¹⁰

⁹ Distribution for BEV based on previous reviewed literature. PHEV and Stationary based on own assumptions)

¹⁰ Please note that the BOM aims to determine the amount of different materials contained in a battery pack. Since a virtual product is calculated, the BOM of different cells from Table 4 are aggregated according to their market share in the specific application. This also leads to an effect that for some cells, the materials e.g. aluminium are listed for each component (collector, casing, etc.), while for other cells only the total amount of aluminium is given. Thus, specific values in the lines might seem comparatively low at some points, while the total amount of materials is correct.

Table 6: BOM for the defined Base Cases (own calculation)

		Base Case	BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7		
		Long Description	Passenger Car - BEV high battery capacity	Passenger Car - BEV lower battery capacity	Passenger Car PHEV	Truck BEV	Truck PHEV	Residential ESS	Grid supporting ESS		
		Pack capacity	Wh	80 000	40 000	12 000	30 000	20 000	10 000	10 000	
		Pack capacity	kWh	80	40	12	30	20	10	10	
Level	Component	Material									
Cell	Cathode	Fe	g	9 293	4 646	4 646	9 293	7 744	6 195	6 195	
		Co	g	9 555	4 778	1 254	2 765	2 090	292	292	
		Ni	g	35 923	17 961	2 613	9 988	4 355	1 160	1 160	
		Mn	g	17 112	8 556	2 589	1 888	4 315	157	157	
		Al	g	510	255	23	113	38	19	19	
		Li	g	14 440	7 220	2 014	4 704	3 357	1 162	1 162	
		P	g	5 153	2 577	2 577	5 153	4 294	3 435	3 435	
		O	g	46 224	23 112	9 160	18 831	15 267	8 004	8 004	
		Carbon	g	8 785	4 393	2 428	5 069	4 047	2 620	2 620	
		PVDF	g	7 130	3 565	1 115	2 941	1 859	981	981	
		Al foil	g	24 847	12 424	4 397	10 991	7 329	4 215	4 215	
	Anode	Graphite	g	87 281	43 641	15 895	36 445	26 492	14 483	14 483	
		SBR	g	1 247	623	487	593	812	345	345	
		CMC	g	1 247	623	266	593	444	345	345	
		Cu foil	g	52 933	26 467	9 093	23 004	15 155	9 103	9 103	
		Al	g	2 283	1 142	-	-	-	-	-	
	Electrolyte	LiPF6	g	9 373	4 687	1 875	4 195	3 125	1 916	1 916	
		LiFSI	g	9	4	-	3	-	0	0	
		EC	g	24 406	12 203	4 688	10 852	7 813	4 820	4 820	
		DMC	g	24 406	12 203	4 688	10 852	7 813	4 820	4 820	
		EMC	g	10 903	5 451	3 370	5 310	5 616	3 257	3 257	
	Separator	PE 10 micron+AL2O3	g	517	258	-	194	-	16	16	
		PP 15 micron + AL2O3	g	2 258	1 129	899	847	1 499	71	71	
		PP/PE/PP	g	7 381	3 691	2 016	4 032	3 360	2 688	2 688	
		PE-Al2O3	g	2 201	1 100	110	550	183	92	92	
	Cell Packaging	Al Tab	g	-	-	250	-	417	-	-	
		Ni Tab	g	-	-	800	-	1 333	-	-	
		PET/Ny/Al/PP/ Laminate	g	435	218	961	163	1 601	14	14	
		Al leads	g	487	243	141	281	234	188	188	
		Cu leads	g	1 406	703	422	844	703	563	563	
		Plastic fasteners/covers	g	1 240	620	188	375	313	250	250	
		Al, Steel, Valve, rivets	g	11 828	5 914	1 132	2 850	1 887	1 412	1 412	
		Al	g	23 135	11 568	7 500	15 000	12 500	10 000	10 000	
		Ni plating Iron	g	12 430	6 215	621	3 107	1 036	518	518	
	Module	Al	g	15 861	7 931	3 814	7 272	6 357	3 975	3 975	
		PP/PE	g	8 510	4 255	1 182	2 914	1 969	1 094	1 094	
		Steel	g	5 749	2 875	1 242	2 474	2 070	1 263	1 263	
		Electronics	g	304	152	63	128	105	64	64	
	System	BMS	Steel	g	9 736	4 868	2 521	4 092	4 201	2 558	2 558
			Copper	g	12 170	6 085	3 151	5 115	5 251	3 198	3 198
			Printed circuit board	g	2 434	1 217	630	1 023	1 050	640	640
		Thermal management	Al	g	21 906	10 953	5 671	9 208	9 452	5 756	5 756
Steel			g	2 434	1 217	630	1 023	1 050	640	640	
Packaging		Al	g	51 114	25 557	13 233	21 484	22 055	5 116	5 116	
		PP/PE	g	3 651	1 826	945	1 535	1 575	3 837	3 837	
		Steel	g	14 604	7 302	3 781	6 138	6 301	15 349	15 349	
		WEEE	g	3 651	1 826	945	1 535	1 575	1 279	1 279	

The approach for defining the BOM for the bases cases will be summed up again in the following, In a first step, depicted in Figure 12, the base cases were built by first reviewing common cells (using different cell chemistry and cell formats) and their BOM on the market (see Table 4). For these different cells the materials in g/Wh was calculated and based on that a virtual product (virtual cell) was built based on the market share of different cell chemistries in the considered application (Figure 6).



Figure 12: Approach for defining a virtual product (on cell level)

After having defined the virtual product on cell level, the great heterogeneity in the case of module and system design has to be captured. Since detailed information, regarding a representative BOM for the modules and system level is hardly available. Therefore, a bottom-up approach was used to build the system around the defined common cells, based on the typical distribution of battery systems and the share cell materials. The process is depicted in the flow chart below (Figure 13).

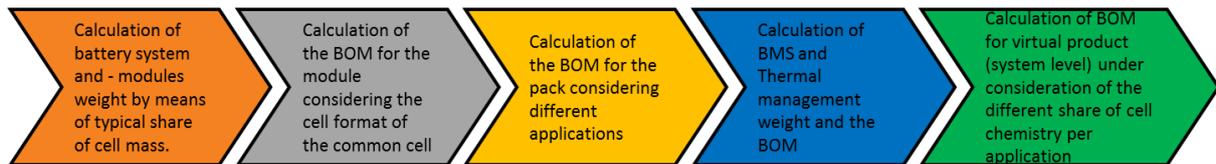


Figure 13: Approach for defining a virtual product on the battery systems level

Based on the total cell mass of the common cells, the mass of the corresponding module and system (packaging) was calculated. Therefore first some values given in literature were reviewed (Figure 7) and also own battery systems were modelled considering different capacities, cell chemistries or mobile applications (Figure 8). Based on these insights finally the weight distribution of a virtual product for the applications was defined (including share of mass of cells, module, BMS, Thermal management and system packaging). After having defined the weight proportion for the module, system packaging, BMS and Thermal management. The corresponding BOM were calculated. For the BOM of the modules the cell format of the (common) cell was considered (Figure 10). While for the systems packaging especially the application play a crucial role and therefore was considered (Figure 11). The BOM for the BMS and Thermal management is considered as similar for all applications. The virtual products for each application, forming the BOM our Base Cases Table 6) is finally again calculated according to the share of cell chemistries within the application.

4.2.2. Assessment of the primary scrap production during sheet metal manufacturing

4.2.2.1. Production process of a LiB

The manufacturing process of a LiB can be roughly divided into four parts: Electrode production, cell assembly, module assembly and battery system assembly. Each of these sub-areas comprises a series of production steps that can easily diverge depending on the desired cell geometry and the intended use of the battery system. The process of battery system production is therefore described exemplarily in the following Figure 14.

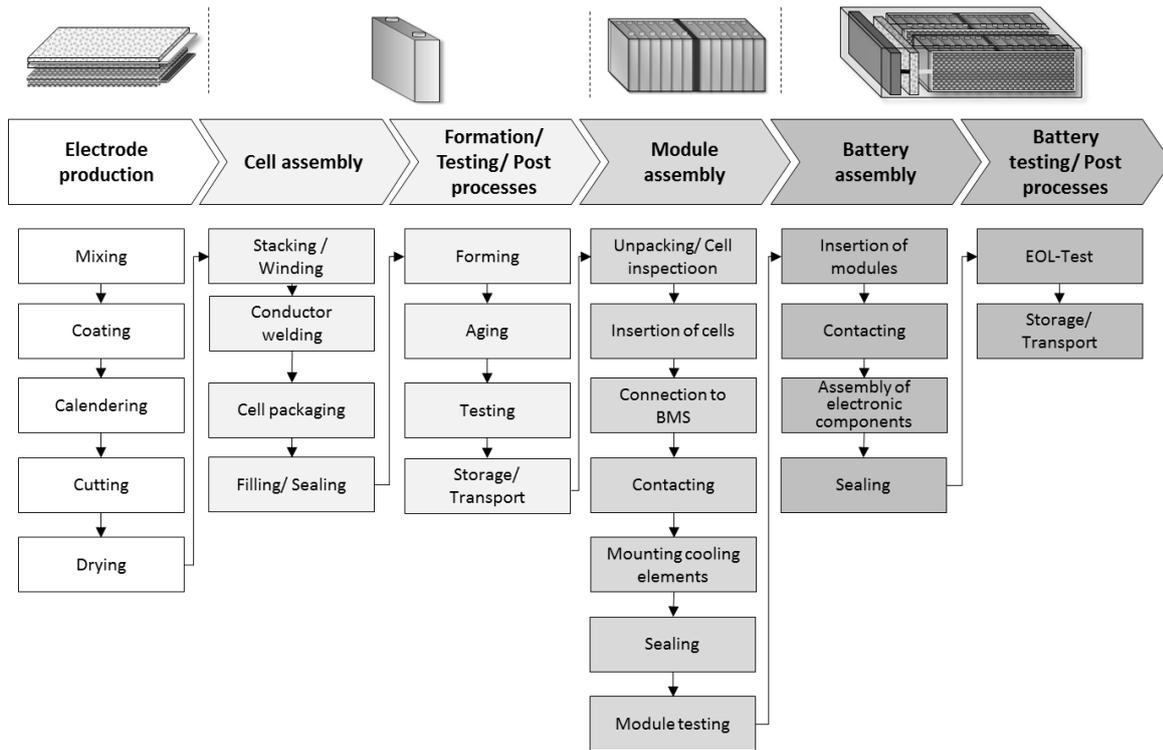


Figure 14: Exemplary lithium ion battery manufacturing process (Hettesheimer et al. 2013)

The individual process steps will be explained in more detail in the following.

Mixing

The starting point of any cell production is the manufacturing of the electrodes. The chemical components of the electrode coating are mixed with binding agents, solvents and additives to form a paste. The mixing process can be carried out in different ways by mixing and dispersing. The difficulty in this process step lies in achieving a high degree of homogeneity despite the disperse solids and maintaining this until the drying process, without the formation of agglomerations (Michaelis et al. 2018; Hettesheimer et al. 2013; Heimes 2014).

Coating and drying

In this process, the coating paste (also called "slurry") is applied to both sides of the carrier films. In the case of the cathode, this is aluminium, while the carrier foil of the anode usually consists of copper. The typical values for the wet layer thickness are between 200-250 μm . The coating width with several application nozzles can be up to 1500 mm. The challenge is to create a homogeneous layer thickness across the entire web width. The drying phase immediately follows the coating process. As a rule, the ovens are between 30 m and 50 m long. Drying not only reduces the moisture content of the slurry, but also evaporates the previously added solvents and either recovers them or recycles them thermally. Compared to coating, drying is the production process that determines the speed. The drying time depends on the thickness of the coating, the solids content of the suspension and the solvent used. Today, circulating air dryers are generally used, partly in combination with infrared dryers. Gentle drying is achieved using temperature profiles with different zones (Kwade et al. 2018; Michaelis et al. 2018; Hettesheimer et al. 2013; Heimes 2014).

Calendering

After drying, the electrode material is wound into so-called "coils". During subsequent calendering, these are unwound again after transport and the electrode thickness is compacted by rotating rollers at a pressure of around 1500 N/mm until a predefined porosity is achieved. The foils are then rolled up again into coils. A homogeneous layer thickness is again important, which is why pressure-controlled calenders are usually used to compensate for any unevenness by varying the pressure accordingly (Hettesheimer et al. 2013; Heimes 2014).

Slitting

After calendering, the coils have a width corresponding to that of the coating line. During cutting, the coils are then cut into 100 mm to 300 mm wide foil strips by means of a rolling knife or laser beam and either rewound into coils or further subdivided into individual sheets. If the cut is made by a rolling knife or punching, there is a risk of the active material peeling off, while laser cutting involves the introduction of heat into the active material and can initiate metallurgical processes. The processing speeds for punching are up to 0.2 s/sheet. Laser cutting achieves speeds of up to 1200 mm/sec (Hettesheimer et al. 2013; Heimes 2014; Michaelis et al. 2018).

Vacuum drying

The later cell quality and life is closely related to the residual moisture of the electrodes during cell assembly. For this reason, the electrodes are separated after cutting, dried for several hours in vacuum ovens according to polarity in stacks and removed again in the drying room for cell assembly (ANL 2012).

Cell assembly

The previously described steps of electrode production are essentially independent of the later cell geometry. However, this changes during the cell assembly phase. After cutting, the cells are either stacked (described in the following) or they are wound. The subsequent packaging and filling/insertion phases are essentially the same for all cell geometries. In the following, the focus is on the assembly of a pouch cell. The entire process of cell assembly takes place in the drying room for reasons of correlation of moisture in the cell with the service life and performance of the battery (Hettesheimer et al. 2013; Heimes 2014).

Stacking

First, the sheets cut from the roll in the previous process are stacked on top of each other. Several layers consisting of anode, separator, cathode, separator, anode etc. are formed. The separator is often folded in rolls after each sheet so that the individual sheets are inserted separately from the side, but the separator remains in one piece until the desired cell thickness is reached. The process is a typical pick & place application where high stack accuracy is required (+/- 0.2 mm) (Kampker 2014; Heimes 2014).

Packaging, electrolyte filling and sealing

Packaging describes the process of inserting the stack of electrodes into the intended packaging. Whereas in the case of pouch cells it is an aluminium foil, rigid cell containers are used for the prismatic cell. After the stack has been inserted, the cell is partially sealed for the subsequent filling process. The main requirement for the cell packaging, which is usually a purchased part, is that it must be impermeable to water vapour diffusion throughout its entire service life. The cell is filled with the electrolyte under vacuum. The precise dosing of the electrolyte and the resulting complete wetting of the electrodes and the separator are of great

importance in this process. They are ensured by weight control. The cell is afterwards temporarily sealed (vgl. ANL 2012; Hetteshheimer et al. 2013; Heimes 2014).

Formation, aging and testing

After the cell has been sealed, formation and all subsequent process steps can take place outside the drying room again. Previously, the cell was uncharged. This now changes due to the initiation of the electrochemical reaction. The lithium ions begin to be embedded in the graphite of the anode and the solid electrolyte interphase (SEI) is formed. The forming process takes around 24 hours (up to 10 days) and significantly determines the service life and safety of the lithium-ion cell. The cell can be contacted either manually or automatically, whereby the cell is charged and discharged several times. Depending on the cell manufacturer, the current strength and the intermediate rest phases vary. The formation is relatively time-consuming and capital-intensive. The final cell sealing takes place after the last formation. The cells are then stored for a longer period during the aging process and tested for self-discharge (ANL 2012; Hetteshheimer et al. 2013; Heimes 2014; Michaelis et al. 2018).

Module assembly

The finished cells are interconnected to modules in the further process. The module assembly is determined by rather typical assembly activities and therefore they will not be explained in detail. The first step in module assembly consists of fixing the cells in the module and contacting. This is usually done by laser beam or ultrasonic welding or by mechanical locking using a spring mechanism. Subsequently, further electronic components are added to monitor the module. In the final step of module assembly, heat conductors may be attached to the module to dissipate the heat generated during operation. Finally, the module is closed and transferred to a quality inspection (vgl. ANL 2012; Kampker 2014).

Battery assembly

All modules that have successfully passed the quality test are assembled into battery systems or battery packs. For this purpose, the modules are anchored in a prefabricated battery case, either in a row or in parallel rows, depending on the battery design. The individual modules are then contacted again (e.g. by a contact rail or busbars). In addition, the battery management system and cooling system are installed and wired. Finally, the finished battery system is sealed and tested (ANL 2012; Hetteshheimer et al. 2013; Thomas et al. 2018).

All-solid electrodes production

The production of all-solid battery electrodes has similarities as well as key differences with the production of LIB electrodes as it is described above. For example, in LMP® technology or other all-solid batteries, the metallic lithium film is laminated on a roll mill to required final thickness. The lithium metal anode does not need a carrier and acts as its own current collector.

The cathode as well as the separator chemical components require mixing in solution for coating or through an extrusion screw. Drying is needed for coating. Homogeneity of composition as well as thicknesses across the film width is as critical as with lithium-ion electrodes. Calendaring may or may not be used depending on the process capability to control thickness. Production of the electrodes in dry rooms may be used to limit the moisture content.

Electrodes “coils” are typically slit into the required width for subsequent cell assembly and packaging. Electrode sheets are typically stacked as for lithium-ion pouch cells, with a repeated sequence of anode – separator – cathode. There is no need to fill the cell with

electrolyte as the polymeric ion-conducting medium is built directly into the cathode and separator films. For that reason, voltage is measured across the cathode and anode as soon as they are put into contact and self-discharge may be monitored across the subsequent production steps. There is also no need for the “formation” step to build the Solid Electrolyte Interface (SEI).

In all-solid technology, individual cells do not require a housing. A group of cells connected together typically in series may however be housed in some form of casing, emptied of moisture and sealed to block water vapour diffusion into this battery module envelope hence preventing the premature degradation of the metallic lithium anodes. Battery modules are typically connected in a series that provides the targeted voltage for the battery application. Such strings of modules may moreover be connected in parallel to form larger battery systems.

4.2.2.2. Energy consumption of battery production

The question of energy use for battery production has been considered in particular in the context of LCA analyses, whereby greenhouse gas emissions are mostly determined in kg CO₂ equivalent per kWh of battery capacity produced (kg CO₂ eq/kWh). Industry data from battery production can hardly be obtained, so that studies from 2011 to 2016 (as in Romare and Dahllöf 2017) pursue different approaches to determining greenhouse gas emissions and energy use in battery production. "Bottom-up approaches" try to estimate the energy input of individual process steps from battery production. The energy input is considered to be rather low (0.4-1.4 kWh/kg per battery pack produced or less than 3 to more than 10 MJ/kWh (Romare and Dahllöf 2017; Yuan et al. 2017; Ellingsen et al. 2017), while "top-down approaches" also include other (auxiliary) processes and are considered more complete. Thereby energy inputs in the range of 350 to 650 MJ/kWh (30 to over 250 kg CO₂ eq/kWh) are estimated (Romare and Dahllöf 2017 and the literature cited therein as well as Hall and Lutsey 2018).

Depending on whether the focus is on the assessment of the energy input in battery cell- and pack production or even on the total primary energy demand for the production of all components (including battery materials), energy requirements of approx. 200 - 2500 MJ/kWh are calculated. In the studies, it is often unclear to what extent only process steps and the electricity demand are taken into account or whether material processing is already/partially included.

A comparison of several studies (Romare and Dahllöf 2017; Pettinger and Dong 2017; Yuan et al. 2017) shows that the extraction and processing of raw materials results in comparatively low emissions. The studies also show no clear differences when considering different cell chemistries. With regard to the energy input for battery materials (components) vs. battery production (processes), it can be seen that both contribute to the energy input in approximately the same dimension. Depending on the study, the contribution of "cell material" vs. "cell production" is between a ratio of 30:70 - 70:30 and is therefore also rather unclear (however, the estimated order of magnitude is the same).

Peters et al. 2017 provides an overview of existing assumptions regarding the energy demand for the production of LiB. For this purpose, 36 LCA studies were analysed and differentiated according to cell chemistry and the approach for identifying the energy demand (top-down, bottom-up or no information). Thereby the cumulative energy demand (CED) of 19 studies was identified and is shown in the following figure at battery pack level.

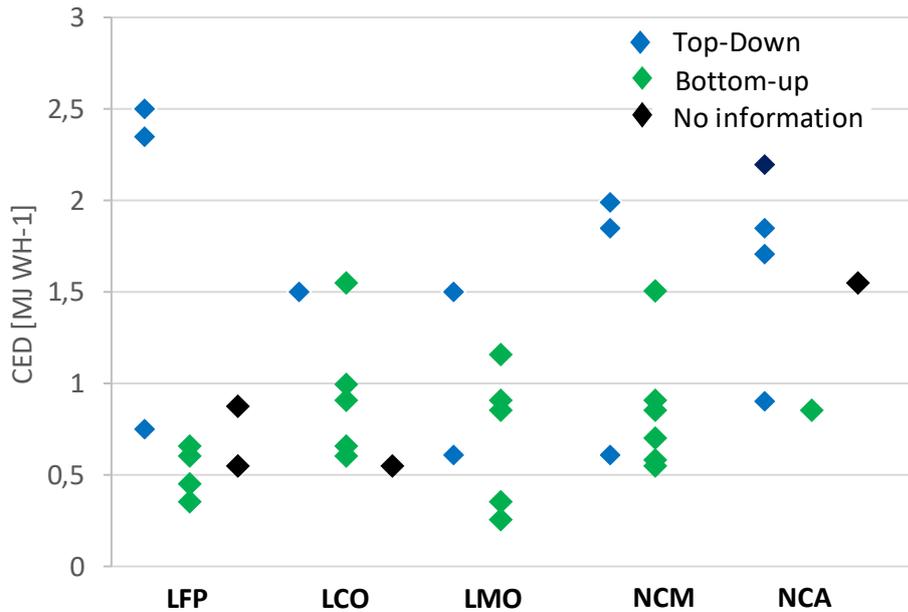


Figure 15: Cumulative energy demand at battery pack level for different cell chemistries (based on Peters et al. 2017)

The figure illustrates again the difficulties mentioned before with regard to the exact quantification of energy demand. Accordingly, there is also a lack of further detailed information on the energy demand in the individual production steps. However, many of the studies point out the fact that the production of battery materials has a large share in energy demand during the electrode production (especially cathode production, see Romare and Dahllöf 2017). For the other (usually less energy-intensive) components, the results of the studies vary. Electrode coating and drying processes (Pettinger and Dong 2017; Yuan et al. 2017) or drying rooms are thereby among the most energy-intensive steps in battery production. Pack production (including electronics, etc.) seems to require just as much energy, while the pack assembly is estimated to be less energy-intensive.

In summary, an energy consumption of 350 to 650 MJ/kWh (less than 100 to max. 200 kWh el. energy for the production of 1 kWh battery) can be assumed for battery production (process steps) (400-600 MJ/kWh are relatively frequently determined in studies). For battery materials or components, the same order of magnitude is assumed again (ratio 30:70 to 70:30 depending on the study, but mostly a lower energy demand on the part of the battery materials is estimated or calculated).

4.2.2.3. Improvement options on side of the battery production

As concluded in the previous section, coating and drying, forming and providing conditioned drying room atmospheres are the most energy-intensive process steps and they account for the major share of energy consumption in cell production. In the following, some improvement options are listed to tackle the main drivers of the energy consumption within these production processes:

Energy efficiency during production - Coating, drying and formation

On the coating and drying side, there are several starting points for reducing energy consumption. On the one hand the solvent content can be reduced up to a dry coating, on the other hand the drying process can be further optimized. A significant cost and energy saving

can be achieved by shortening the time in the drying process. The aim is to produce suspensions with a higher solids content. Dry coating might be available for the mass market from 2025 onwards. An alternative approach might also be the PVD coating. An acceleration of the drying process and a multiple use of the drying section would also be thinkable in order to reduce investment and energy costs. This means an "initial drying" of the first side, so that carrier rollers can be used for transport and after the subsequent coating of the second side, the total drying of both sides can take place simultaneously (Michaelis et al. 2018).

Potential for energy efficiency and cost savings during formation can be achieved due the fact that forming plants have high-connected loads in continuous operation. For this reason, it is necessary to reduce energy losses during forming as much as possible. The concept of using the energy released during the discharge of one lithium-ion cell to charge another is being applied already (Michaelis et al. 2018).

Design for disassembly and design for recycling

Although this is not a part of the production of battery systems, the possibility for remanufacturing and recycling of batteries is strongly determined during the production phase. To facilitate the disassembly and later on the reuse or the recycling of the battery packs, a "design for disassembly" and "design for recycling" could offer a high benefit. Improvements in this direction could address different issues as how different components are connected, how cells or packs are designed and to what degree information about the pack or the cell is made transparent.

Currently, the state-of-the-art technologies used to connect the structural components are screwing, bonding and welding of the individual elements. Especially the bonding and welding could be considered as unfavourable in terms of "design for disassembly" compared to reversible joints (Michaelis et al. 2018).

In addition, considering the steady growing number of battery systems considerable for a later disassembly, recycling or reuse, automation will play a major role to manage these large amounts in an economical way. Hereby the large variety of battery cells, battery modules and battery system systems currently in use constitutes a major challenge for automated dismantling (Michaelis et al. 2018). There may be variations in the materials used, the design, the location of the battery and the shape of the battery pack. Although a full standardisation is considered as unrealistic, a number of basic standards could make battery disassembly and recycling less time-consuming. For example, tools or lifting parts (e.g. eyelets or mounting threads) could be installed as standard in future battery packs. This would allow standard lifting to be used to disassemble the battery pack (Thomas et al. 2018; European Environment Agency 2018). Considering the specific cell designs, the cells could also be designed in a way that the material can be recovered in its processed form (Romare und Dahllöf 2017).

Another issue is the marking of the cells to provide transparent information about the materials used in the battery pack or cell. The design requirement in this respect is a way to also enable easier recycling with a potentially higher material recovery and higher quality (Romare und Dahllöf 2017).

Thus, by adapting the design, the disassembly and recycling process could be simplified and the recovery of materials optimized. However, the demands on installation space and performance are countering this development. Modularization, substitution of adhesives and a reduction of the module voltage are conceivable, but contrary to the current development

(Michaelis et al. 2018). A more detailed section about the requirements to support disassembly, recyclability and reusability can be found in the task 7 report¹¹.

Energy mix

The environmental impact of cell manufacturing is partly dictated by the energy sources used to generate the electricity. Since the greenhouse gas emissions associated with the use of energy are highly dependent on the energy mix, the environmental impact of battery production improves accordingly with the proportion of renewable energies in the electricity mix (Thomas et al. 2018).

4.2.3. Packaging materials

The transport of dangerous goods and articles in Europe is arranged in the ADR by UNECE (ECE/TRANS/257)¹² and the IATA¹³. Batteries fall under class 8 (corrosive products) or, for lithium and Li-ion batteries under class 9 (miscellaneous).

Lithium batteries are classified in Class 9 – Miscellaneous dangerous goods as:

- UN 3090, Lithium metal batteries; and
- UN 3480, Lithium ion batteries

or, if inside a piece of equipment or packed separately with a piece of equipment to power that equipment as:

- UN 3091, Lithium metal batteries contained in equipment; or
- UN 3091, Lithium metal batteries packed with equipment; and
- UN 3481, Lithium ion batteries contained in equipment; or

UN 3481, Lithium ion batteries packed with equipment.

For lithium (ion) batteries a specific section exists in the ADR (§2.2.9.1.7) with exigencies to these batteries:

- Lithium cells and batteries have to pass ‘Manual of Tests and Criteria, part III, sub section 38.3’.
- Cells and batteries must have a safety venting device or being designed that no violent rupture can occur.
- Each cell and battery are equipped with an effective means preventing external short circuit.
- Each battery with cells or strings of cells in parallel are equipped with an effective means preventing a dangerous current in the opposite direction, e.g. by diodes or fuses.
- Cells and batteries must be manufactured under a production quality management system.

¹¹ Please note, that furthermore JRC (DG JRC-B.5) is conducting research activities related to the assessment of material efficiency aspects of other Energy-related Products (ErP) and the analysis and development of methods supporting the definition of product-specific requirements <http://susproc.jrc.ec.europa.eu/E4C/index.html>

¹²https://www.unece.org/fileadmin/DAM/trans/danger/publi/adr/adr2017/ADR2017E_web.pdf

¹³<https://www.iata.org/whatwedo/cargo/dgr/Documents/lithium-battery-guidance-document-2017-en.pdf>

Table A in the ADR prescribes the needed marking, the special provisions and the packaging possibilities. Chapter 6 prescribes the packaging tests and pass criteria.

For lithium batteries a distinct category is made for damaged or defective cells or batteries, defined as that they do not conform to the type tested according to the provisions of the Manual of Tests and Criteria.

- Cells or batteries must be protected against short circuits.
- Cells or batteries must be secured in the packaging to prevent damage for protection against movement (e.g. vibrations)
- Robust outer packaging, according to packaging group II
- Clearances within the packaging must be filled with cushioning materials of non-conductive material, non-flammable material can be lined
- shall not be transported through Category E tunnels.
- are classified and marked accordingly:
 - Lithium ion batteries, UN 3480 WASTE LITHIUM-ION BATTERIES, Class 9, II
 - Lithium-ion batteries UN 3481, packed in devices or with devices,
 - Class 9, II
 - Battery-powered vehicle / battery-powered device UN 3171, Class 9
- require additional transport documents and permits (e.g. ADR transport permit), and special driver training courses

A guide of the EPTA (European Power Tool Association) has been published in cooperation with the ZVEI (Zentralverband Elektrotechnik- und Elektronikindustrie e. V.), which provides the most important information on the transport of batteries. Although this guide refers explicitly to the transport of electric tools and electric gardening equipment, it reflects in a very general way the conditions for the transport of batteries. The following flow-chart gives a structure to determine the appropriate packaging (ZVEI & EPTA 2018).

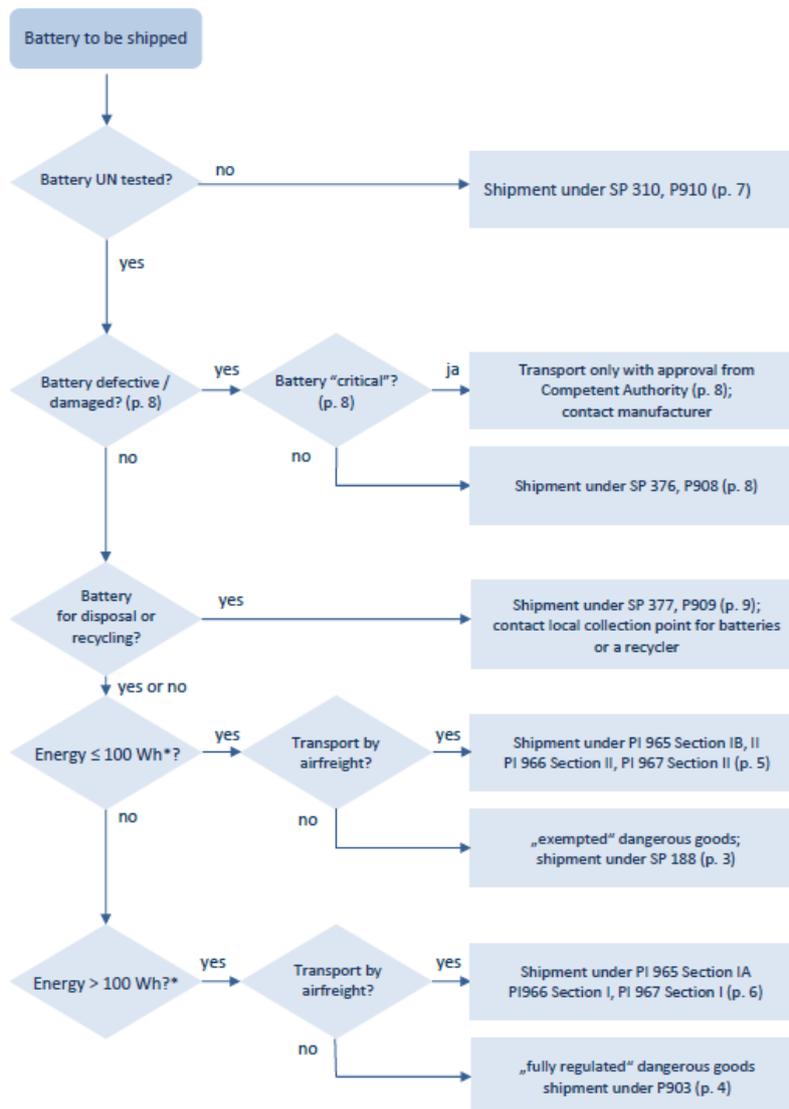


Figure 16: Flow-chart to determine the appropriate packaging (ZVEI & EPTA 2018)

In particular, the energy content and the different conditions classify which dangerous goods regulations must be observed when transporting lithium-ion batteries. Due to exceptions, simplified requirements apply, e.g. for lithium-ion batteries with an energy content of up to 100 Wh. Lithium-ion batteries with an energy content of more than 100 Wh, on the other hand, must always be treated as fully regulated dangerous goods class 9.

Table 7: Transport issues (Example) (ZVEI & EPTA 2018)

Transportation Mode	Road / Rail (ADR/RID), Sea Freight (IMDG Code)		
> 100 Wh (per battery)			
Batteries	(without equipment)	Batteries packed with equipment (at least one battery which is not attached to tool)	Batteries contained in equipment (contained/plugged-in in tool)
Packing Instructions	P903, LP903		
Max. quantity	333 kg per transport unit (truck incl. trailer) for exemptions according to ADR 1.1.3.6		
Weight limit	n/a		
Packaging	Batteries must be placed in inner packaging that completely enclose the battery, batteries must be protected to prevent short circuits. Batteries must be secured against movement within the outer packaging. UN approved packaging (Packing Group II: e.g. UN/4G/Y30/...)	Strong outer packaging Protection against unintentional activation Short circuit protection	
Marking 2	Hazard label № 9A (10x10 cm) ADR: UN 3480 IMDG Code: UN 3480 LITHIUM ION BATTERIES	Hazard label № 9A (10x10 cm) ADR: UN 3481 IMDG Code: UN 3481 LITHIUM ION BATTERIES PACKED WITH EQUIPMENT or UN 3481 LITHIUM ION BATTERIES CONTAINED IN EQUIPMENT	
Sea freight container marking	CONTAINER-PLACARDS (min. 25x25 cm)		
Transport document	UN 3480, LITHIUM ION BATTERIES, 9, (E) Number of packages and packaging type (e.g. 1 Fibreboard box) Battery weight	UN 3481, LITHIUM ION BATTERIES PACKED WITH EQUIPMENT, 9, (E) Number of packages	UN 3481, LITHIUM ION BATTERIES CONTAINED IN EQUIPMENT, 9, (E) Number of packages and packaging type (e.g. 1

	(e.g. xx kg), Shipper & consignee's address Sea freight (IMDG Code): (language English) IMO-DANGEROUS GOODS DECLARATION (SOLAS 74, KAP. VII, REG 5, MARPOL 73/79, ANNEX III REG. 4 OF IMDG-CODE)	and packaging type (e.g. 1 Fibreboard box) Battery weight (e.g. xx kg) Shipper & consignee's address Sea freight (IMDG Code): (language English)	Fibreboard box) Battery weight (e.g. xx kg) Shipper & consignee's address Sea freight (IMDG Code): (language English) IMO-DANGEROUS GOODS DECLARATION (SOLAS 74, KAP. VII, REG 5, MARPOL 73/79, ANNEX III REG. 4 OF IMDG-CODE)
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As indicated in the table: "Batteries must be placed in inner packaging that completely enclose the battery, batteries must be protected to prevent short circuits and batteries must be secured against movement within the outer packaging".

Currently different types of boxes are sold for this task. Some are mainly made of wood or fibre box, while others are made of aluminium (especially for used or damaged batteries). Furthermore, company unique variants exist.

4.2.4. Materials flow and collection effort at end-of-life

The following Figure 17 depicts the flow of battery materials as well as different possible end-of-life options for the batteries. In this subchapter the sourcing of raw materials, the possibility of 2nd-life applications and finally the recycling of used batteries will be described in more detail.

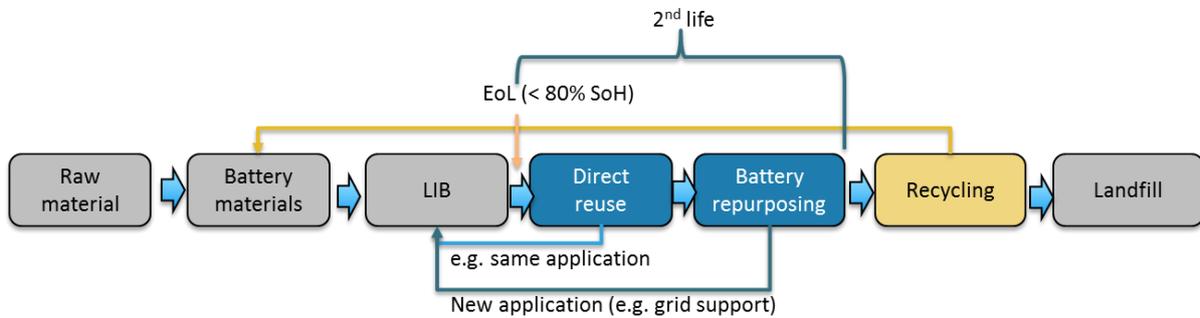


Figure 17: End-of-life options for LiB (based on European Environment Agency 2018)

4.2.4.1. Raw material sourcing

The potential for covering the demand by domestic sourcing in Europe can be considered (apart from cobalt mainly in a refined form) as very limited (see Figure 18). This is especially the case for key materials as nickel, natural graphite manganese or lithium.

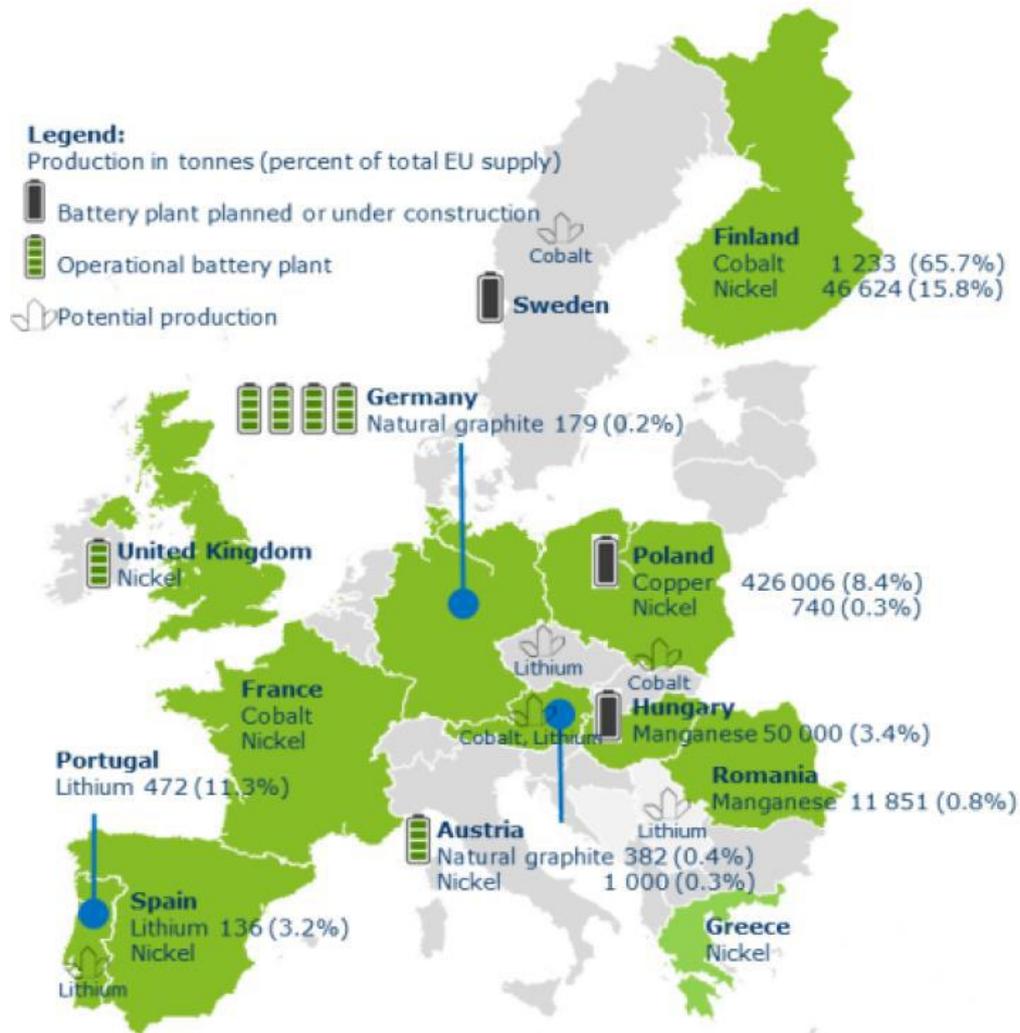


Figure 18: Mine production and potential of battery raw materials, and battery plants in the EU11 (European Commission 2018)

Besides the economic value of these materials most of them, except for lithium, are also considered as "critical raw materials" (Lebedeva et al. 2016). This becomes even more important under the consideration that the global share of EU raw material production for key LiB materials is comparatively low as Table 8 indicates.

Table 8: Production and sourcing of primary battery raw materials (European Commission 2018)

Raw materials	Major global producers	Major sources of EU supply	EU production	Import reliance rate	EoL recycling input rate
Cobalt	D.R. Congo (64%) China (5%) Canada (5%) 135 500t	Finland (66%) Russia (31%) 1900t	Finland	32%	35%
Lithium	Chile (44%) Australia (32%) Argentina (11%) 25 500t	Chile (66%) Portugal (11%) United States (9%) 4200t	Portugal Spain	86%	0%
Nickel	Indonesia (24%) Phillipines (16%) Australia (10%) Canada (10%) New Caledonia (7%) 2 255 500t	Russia (20%) Finland (16%) United Kingdom (13%) Norway (8%) 293 400t	Austria Finland France Greece Poland Spain United Kingdom	59%	34%
Natural graphite	China (69%) India (12%) Brazil (8%) 1 100 000t	China (63%) Brazil (13%) Norway (7%) 95 000t	Austria Germany	99%	3%

The low EU production and thus the high import rate for these key materials also leads to supply risk for those materials. The following table lists the supply risk for different battery materials. The weighting factors hereby indicate the relative importance of each indicator to the overall supply risk score as given in Helbig et al. 2018.

Table 9: Relative supply risk indicator for different raw materials (based on Thomas et al. 2018; Helbig et al. 2018)

Criterion	Indicator	Weight	Li	Co	C	Mn	Ni	Fe	Cu	Al
Risk of Supply restriction	Static reach reserves	8,90%	Green	Yellow	Green	Red	Red	Red	Orange	Yellow
	Static reach resources	5,20%	Green	Green	Green	Yellow	Red	Red	Yellow	Orange
	End-of-Life recycling rate	9,20%	Red	Green	Red	Yellow	Green	Green	Yellow	Green
Risk of demand increase	By-product dependence	3,90%	Yellow	Red	Green	Yellow	Yellow	Green	Yellow	Green
	Future technology demand	14,10%	Red	Yellow	Green	Green	Green	Green	Green	Green
	Substitutability	14,20%	Green	Green	Yellow	Red	Yellow	Green	Orange	Green
Concentration risk	Country concentration	9,70%	Orange	Orange	Red	Green	Green	Yellow	Green	Orange
	Company concentration	13%	Yellow	Yellow	Red	Green	Green	Green	Green	Orange
Political risk	Political stability	11,20%	Green	Red	Yellow	Green	Yellow	Green	Green	Yellow
	Policy perception index	5,20%	Green	Red	Red	Yellow	Orange	Green	Green	Green
	Regulation risk (HDI)	5,30%	Green	Red	Yellow	Yellow	Yellow	Green	Green	Yellow
Relative overall supply risk			Red	Red	Yellow	Yellow	Green	Green	Green	Green

Based on the given indicators it can be concluded, that there is the highest supply risk for lithium and cobalt and a medium risk for the supply with (natural) graphite, manganese, nickel and iron. Considering the potential supply risks, the extension of the service life of the materials/batteries and their return to the material cycle plays an important role.

4.2.4.2. Second-life applications

The performance of lithium-ion battery cells and battery systems, in terms of energy storage capacity and round trip efficiency and power, decreases in the course of time due to cycling, elevated temperature and time-calendar aging (Podias et al. 2018). The battery system of an EV mostly reaches its End of Life when the remaining capacity falls below 70-80% SoH. Automotive lithium-ion batteries as well as LMP batteries offer the possibility of reuse in stationary storage applications after the vehicle's service life (although the electronics might constitute a barrier). When batteries are removed from electric vehicles after their first life, they are likely to retain significant capacity, typically 70%-80% of their original capacity. According to the European Directives (End-of-Life Vehicles Directive 2000/53/EC and Battery Directive 2006/66/EC) batteries must be collected and recycled¹⁴, but their residual capacity could be further used in other applications as e.g. storages for supporting the power grid (Hall and Lutsey 2018). The following figure indicates these different options.

¹⁴ In particular, 45% of LIBs must be collected and at least 50% of the average weight of LIBs should be recycled.

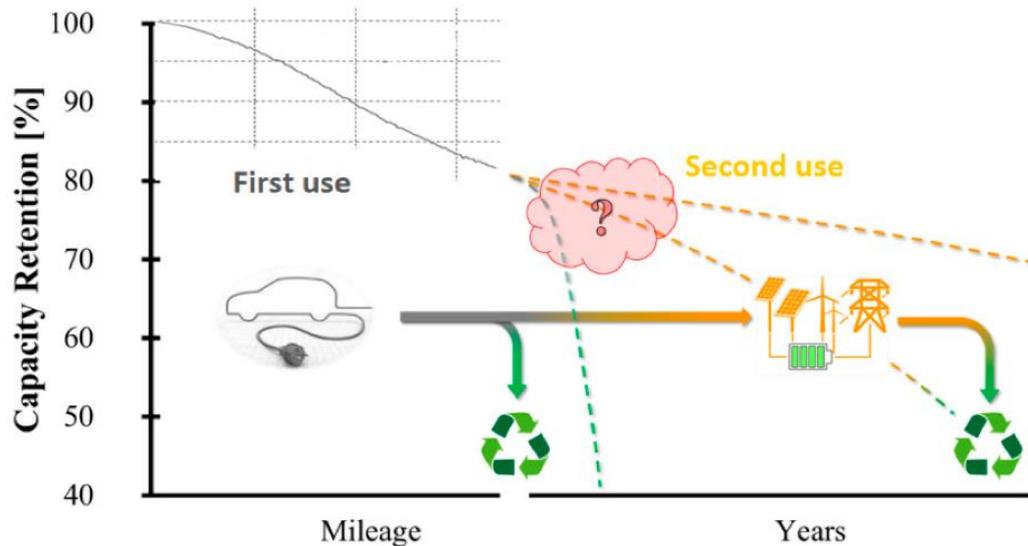


Figure 19: Options after the first-life of the battery (Podias et al. 2018)

In terms of second use it can be distinguished between two different strategies: 1) the battery system is not dismantled, tested and, if suitable for second use, reused directly, 2) the battery system is dismantled at module level and a new battery system is created (Bobba et al. 2018). This second strategy is called "battery repurposing", while the first strategy is called "direct reuse" (Ardente et al. 2018). The possibility of a direct reuse without dismantling the whole battery system it is the preferable option out of an economic and environmental perspective. If not possible, the battery system can be dismantled and the modules/cells could be tested and repurposed in a new battery system with new materials/components, e.g. BMS. Battery repurposing will require new materials/component, for instance a new battery tray since they are not designed for dismantling, and thus an increase in the costs associated with repurposing step, but the change of use of the battery will be more flexible and designed for specific applications. Paul et al. 2015 define battery repurposing can be defined as a process that includes breaking down packages into modules, checking the hardware of the modules, performing inspection and health benchmark tests on the modules, and certifying that the modules meet a market-defined Second Life standard. After certification of the modules, the second process, repackaging, takes place. In the repackaging process, modules that are considered "good enough" for second use are placed in sub-packaging and packaging that can be shipped for use in stationary systems. It is also possible that very good modules for EVs can be directly reused (Cusenza et al. 2018).

Up to now due to the different possible applications, products (as cell chemistries) or even the energy mix it is hard to give a clear answer on the general advantage of second life applications. Anyhow, some extensive studies have been undertaken to evaluate those possible benefits. In the following the main results of two most grounded studies will be provided. The results from the project: "Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB)" (Cusenza et al. 2018) and "Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries" (Neubauer et al. 2015).

First of all, in the SASLAB-project, the results have shown that the second use of EV batteries is feasible from a technical point of view. As regards the environmental assessment, an adapted Life Cycle Assessment (LCA) has been developed to assess the environmental performance of EV batteries in secondary use. This method was applied to two different case studies: Peak shaving of an office building in Ispra (IT) and increase of own consumption of

photovoltaic (PV) in a residential building in the Netherlands. For the application of the peak shaving, the results indicated that a reusable LMO/NMC battery is only environmentally friendly if it replaces a new battery (either an LMO/NMC or a Lead Acid battery). Adding a repurposed battery in a building where no batteries have been used before does not bring any benefits. Environmental benefits are also observed with increasing PV self-consumption of a residential home: A second-used battery instead of a new one (either LMO/NMC or Lead Acid battery) brings environmental benefits by avoiding battery production (with fresh LMO/NMC battery) or the higher performance of the lithium-ion battery (compared to a PbA battery).

The report from the National Renewable Energy Laboratory identifies that the subsequent service life for the second use is very sensitive to the second life cycle, climate, battery thermal management and other factors, but under favourable conditions and using a discharge cycle depth of 60% of the battery's original capacity may exceed 10 years. The most promising application identified for secondary batteries is the replacement of grid-connected combustion turbine peaker units and the provision of peak shaving services. Compared to automotive service, the use in this application results in relatively advantageous duty cycles, typically significantly less than one cycle per day with discharge times in excess of one hour. Under these conditions, battery life for second use is expected to be in the order of 10 years. Widespread use of batteries in this application would increase the lifetime use of the battery by 72%. Furthermore, it was reported, that technician labour is a significant cost factor for the repurposing that need to be minimised. Therefore, it is not economically viable to replace defective cells within modules, and therefore it is critical to minimize the purchase of modules with defective cells. The use of vehicle diagnostic data to support the purchase of used batteries is therefore of great value to resellers. When such data is available, conversion costs can be as low as 17€/kWh nameplate (Hall and Lutsey 2018; Neubauer et al. 2015).

Up to now there is great uncertainty regarding battery second life performance capabilities and business cases. To enable a successful integration of second-life applications in the products life-cycle still some barriers have to be tackled and improvement options defined:

- If the perspective is the reuse of the xEV battery after its use in EV, a more flexible BMS could ease its use for a potential second-use; in this sense, “design for disassembly” becomes a relevant issue. This refers for example to the to the former mentioned point that the state-of-the-art technologies used to connect the structural components are screwing, bonding and welding of the individual elements. Whereby especially the bonding process could be considered as unfavourable with regard to the reuse (Michaelis et al. 2018).
- Another option is to design the battery to maximize the value throughout its life cycle. The establishment of a BMS in xEVs with the ability to store all important data from the operational history of the battery pack, (e.g. operating temperature, average driving distances, and the habits of individual drivers) at individual battery cell level (in particular temperature, voltage, discharge depth (DOD), state of charge (SOC) is therefore a major issue (Cusenza et al. 2018). By knowing these historical data, for each cell, module or system a suitable application can be defined or they can be grouped according to their individual characteristics, which facilitates an efficient management e.g. by a BMS. Besides the mentioned requirements regarding the available data, also the access to this data has to be enabled.
- The design of electronics in today's battery systems is strongly application-focused. Accordingly, this is only intended for one application at a time. The design of electronics for use in automobiles and in stationary applications would make it possible

to move the battery to its second use without making any major concessions with regard to the required performance. At the same time the electronics must fulfil the automotive requirements such as a service life of at least 10 years, 10,000 operating hours and 300,000 km. On the other hand, also requirements for the stationary applications such as a service life of 20 years and one operation 24 hours a day, 7 days a week (Thielmann et al. 2017).

- Concerning Li-ion xEV batteries, an appropriate and safe removal, handling and transport of such batteries is needed and could minimize the failure rate of repurposing operations. Then, both specialization of operators who can safely manage batteries and strengthening of stakeholders network are two relevant aspects for potentially ease the second-use of xEV batteries (Cusenza et al. 2018).

The role of second life in the future is seen quite different: some expect very few batteries to have a second life, considering that prices for lithium-ion batteries will further drop in the future, while others expect most batteries to have a second life before recycling. Although uncertain, Bloomberg New Energy Finance predicts that by 2025, 27% of these batteries might have a second life in stationary storage, while the remaining 73% would be available for recycling (Drabik and Rizos 2018; Lebedeva et al. 2016).

4.2.4.3. Recycling

Along with the growing number of electric vehicles and stationary batteries, more and more batteries will be available for end-of-life treatment. In the cases where the SoH is too poor, to enable reuse or repurposing, the batteries have to be recycled (Thomas et al. 2018). As mentioned, some of the battery materials are considered as "critical raw materials". Yet, none of these materials is mentioned in the Battery Directive so far. Thus, there are also no requirements (as a specific collection or recycling rate) for the recycling of these materials (Stahl et al. 2018). Currently recycling processes focus on the recovery of the most valuable materials as Ni and Co. Next to the high commodity prices for these materials, a future shortage is expected due to the steadily increasing production of lithium-ion batteries. Thus, battery recycling and circular economy will have an increasingly important role to play and not only valuable materials should be recycled but also those of minor value.

Recycling processes for LIB are a combination of different individual processes: Pre-treatment (deactivation, dismantling and thermal treatment/mechanical separation), pyrometallurgical, mechanical and hydrometallurgical treatment. Thus, different possible recycling routes are existing.

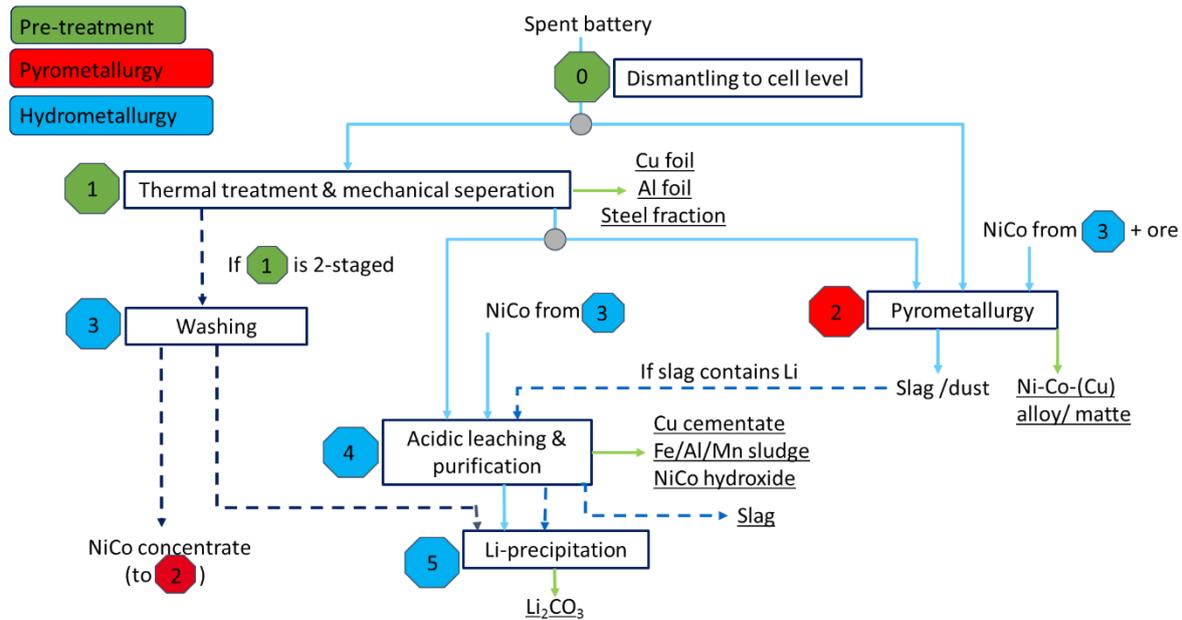


Figure 20: Different possible recycling routes (based on Friedrich and Peters 2017)

The pre-treatment contains several steps as e.g. the deactivation of the system. This can be done by discharging the entire battery system, the battery modules or the battery cells. The dismantling of the battery system and the mechanical separation of the materials. The pyrometallurgical process involves the recovery of metal from the electrode materials with the help of thermal processes, which is why this process is similar to the physical processes. It is an option after the pre-treatment of the batteries and is based on a thermal treatment of the materials. Therefore they are smelted e.g. in a shaft furnace (Gaines 2014) or an electric arc furnace. The treatment binds the heavy metals cobalt, copper and nickel in a melt, while all other contained metal components are completely slagged and subsequently deposited in a landfill. The hydrometallurgical treatment is applied for the direct recovery of metals, such as Co, Ni, Mn, and Li, from the mechanical separated coating materials as well as for the extraction of Al and Li from the slag of pyrometallurgical processes. To achieve this, leaching and several preparation processes are employed (Diekmann et al. 2017). Another possibility is the direct recycling that already has been demonstrated for several cathode types. Thereby the battery materials are recovered for reinsertion into the battery supply chain with little or no additional processing. Discharged cells are placed in a container to which CO₂ is added, and the temperature and pressure are increased to bring the CO₂ above its critical value. The supercritical carbon dioxide extracts the electrolyte from the cells, which can be separated from the gaseous CO₂, and could also be reused after treatment. The electrolyte-free cells are then further crushed under exclusion of water and oxygen. The cell components can be separated by using the different conductivity, density or other properties of the components. Before further use, the cathode materials may require further re-lithiation (Gaines 2014).

Thereby, depending on the selected recycling route (as depicted in Figure 20) different materials can be recovered during the recycling process, what also has an effect on the use of energy, chemicals/additives and the generation of by-products. The following table gives a summary of the different routes, the main processes used and materials recovered.

Table 10: Qualitative assessment of different recycling routes (based on Friedrich and Peters 2017)

Path	Steps	Main processes	Recovered Metals	Energy	Chemicals/ Additives	By-product generation
1	0 (1) 2	Pyrolysis in rotary kiln, EAF & converter	Ni, Co, Cu, (Fe)	high	low	high
2	0 2	Smelting in shaft furnace	Ni, Co, Cu, (Fe)	medium	low	high
3	0 1 2	Thermal treatment + Mechanical separ. Pyrometallurgy	Ni, Co, Cu	high	low	medium
4	2	Direct smelting in EAF	Ni, Co, Cu	high	low	high
5	0 1 4 5	Pyrolysis, Mechanical + Hydrometallurgy	Ni, Co, Cu, Fe, Mn, Li	high	high	low
6	0 (1) 4	Mechanical (inert gas) + Hydrometallurgy	Ni, Co, Cu	medium	high	low

The overall efficiency of battery recycling can be seen as a combination of the collection rate and the recycling efficiency. The collection rate expresses the proportion of lithium-ion batteries produced and collected at the end of their life, while the recycling efficiency is expressed as the percentage by weight of materials that are recovered from the collected waste and then can be reused directly in battery production or in other applications or processes (Lebedeva et al. 2016). While the collection and recycling of batteries is regulated under the Directive 2006/66/EC, which is currently under revision¹⁵. The current Battery Directive is not providing any further details on the collection of those industrial batteries, which are used by private consumers (e.g. electric vehicles, energy storages or e-bikes). However, the recycling efficiencies for the recycling of Li-ion batteries and their battery materials are estimated to be ~ 95 % for Co and Ni, 80 % for Cu and 50 % for Al, depending on the specific process (Stahl et al. 2018). For the pyrometallurgical process (based on electric arc furnace) Diaz et al. 2018 estimate a 61 % recycling efficiency and the following theoretical values given in Table 11 for the hydrometallurgical treatment by leaching of the electrode powder (step 4 & step 5 in Figure 20).

¹⁵ The Directive is from 2006, at which time some developments such as high-energy LiB were not foreseeable and the Directive accordingly has shortcomings in the management of these batteries (Stahl et al. 2018).

Table 11: Theoretical recycling efficiency for specific materials (based on Diaz et al. 2018)

Product	Graphite product ¹⁶	Cu-powder	Fe/Al residual	Co-, Ni-, Mn-hydroxides	Li ₂ CO ₃
Purity	High	Moderate	Moderate	High	High
Recycling efficiency ¹⁷	~100%	~97%	~ 70% for Al/ ~ 90% for Fe	~ 96% for Co, Ni, Mn	> 56%

These values are also mostly in line to assumptions given by Lebedeva et al. 2016. The following table gives an overview of the recycling efficiency of different processes, also considering different cell chemistries:

Table 12: Recycling efficiency of recycling processes (Lebedeva et al. 2016; Hill et al. 2018)

	Combination of pyrom. & hydrom. processes - NMC and LFP [%]	Purely hydrometallurgical process - NMC only [%]	Purely hydrometallurgical process - LFP only [%]
Lithium ¹⁸	57	94	81
Nickel	95	97	NA
Manganese	0	~100	NA
Cobalt	94	~100	NA
Iron	0	NA	0
Phosphate	0	NA	0
Natural graphite	0	0	0
Aluminium	63	-	-
Copper	41	-	-

Based on the above, the following recycling rates will be applied in this preparatory study.

¹⁶ Also graphite is mostly not recovered by recyclers and if so not in battery grade quality.

¹⁷ Specific recycling efficiencies refer on specific product in relation to raw material.

¹⁸ In current practice only 1% of lithium is recovered (<https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle>) (<https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle>)

Table 13: Overview recycling rates Business As Usual (BAU), improved and ambitious scenario (based on diverse literature sources found with EV battery specific data)

Scenario	Cobalt	Graphite	Manganese	Nickel	Lithium
BAU	16.00 ⁽¹⁾	0.00 ⁽¹⁾	0.00 ⁽²⁾	16.00 ⁽³⁾	0.00 ⁽⁴⁾
Improved: 65% collection rate + combination of pyrom. & hydrom. processes ⁽⁵⁾	61.10	0.00	0.00	61.75	37.05
Ambitious: 85% collection rate + purely hydrometallurgical process ⁽⁵⁾	84.15	0.00	84.15	82.45	79.90

⁽¹⁾ Lebedeva et al., 2016

⁽²⁾ Ellingsen & Hung, 2018; Friedrich & Peters, 2017 as quoted in Drabik & Rizos, 2018.

⁽³⁾ Nickel shows comparable recycling efficiency rates as cobalt (Lebedeva et al, 2016; Hill et al. 2018) and recycled content and recycling rates of a similar order of magnitude in general (meaning based on not EV battery specific data) as cobalt based on the UNEP status report from 2011 on recycling rates of metals. Therefore, the same recycling rate has been applied to nickel as cobalt for the BAU scenario.

⁽⁴⁾ Ellingsen & Hung, 2018

⁽⁵⁾ The collection rates are taken from Drabik & Rizos (2018) and the recycling efficiency rates from Lebedeva et al (2016) and Hill et al. (2018). The recycling rates are calculated by multiplying the collection rate with the recycling efficiency rate.

The high variance of possible recycling routes also leads to the effect, that most recycling companies have their own specific recycling process. The following table gives an exemplary overview of recycling activities all over the world, as well as information about the recycling process, the recovered materials and the recycling volume.

Table 14: Overview of recycling companies and corresponding recycling processes (Romare and Dahllöf 2017; Lebedeva et al. 2016)

Company	Facility location	Battery types	Recycling process	Materials recovered today	Recycling volume, tonnes of batteries per year
Accurec	Germany (x2)	NiCd, NiMH, Li-ion	Pyrolysis and hydrometallurgy.	Aluminium, copper, iron scrap, iron/magnesium, and nickel/cobalt.	1500-2000
AkkuSer	Finland	NiCd, NiMH, Li-ion, Zn alkaline	Crushing, chemical treatment	Nickel, cobalt, manganese, iron, copper, aluminium	1000 (li-ion) 4000
AERC Recycling Solutions	USA (x3)	All types including Li-ion and Li metal	Pyrometallurgy		
Batrec	Switzerland	Li	Pyrolysis, pyrometallurgy.	Ferromanganese, zinc.	200

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Euro Dieuze (Veolia)	France	Li-ion	Hydrometallurgy		200
G&P Batteries	UK	Various (incl. Li-ion)	Pyrometallurgical or hydrometallurgical.		
Glencore (formerly Xstrata)	Canada (x2) Norway	Li-ion	Pyrometallurgical with hydrometallurgical treatment of slag and electrowinning		7000
Hunan BRUNP	China	Various (incl. NiMH, Li-ion)	Hydrometallurgy		3600-1000 >6000
JX Nippon Mining and Metals	Japan	Various (incl. Li-ion)	Pyrometallurgy		5000
Nippon Recycle Center corp	Japan (x3)	NiCd, NiMH, Li-ion, alkaline	Pyrometallurgy		
Recupyl	France Singapore	Li-ion	Mechanical separation, hydrometallurgical leaching and refining.	Aluminium, cobalt, stainless steel, lithium products.	110
Retriev Technologies	Canada USA (x2)	Li metal, Li-ion	Hydrometallurgy		4500
Shenzhen Green	China	NiMH, Li-ion	Hydrometallurgy		2000-3000
SNAM	France	NiCd, NiMH, Li-ion	Crushing, pyrolysis, distillation, pyrometallurgy.	Cadmium, ferronickel alloys, ferrocobalt alloys	300
Sumitomo Metals and Mining Co	Japan	Li-ion	Pyrom.refining process followed by a hydrometallurgical leaching and refining process	Nickel, copper, cobalt	Sumitomo Metals and Mining Co
Umicore	Belgium	Li-ion, NiMH	Pyrometallurgical smelting followed by hydrometallurgical refining.	Cobalt, nickel	7000
Veolia	France				

Since in the context of this report it is not possible to describe all recycling activities, only some selected European activities will be described in more detail. Umicore uses a pyrometallurgical treatment with a subsequent hydrometallurgical process. The pyrometallurgical treatment produces slag, a liquid metal alloy, flue gas and gas emissions. The slag fraction, which contains aluminium, lithium and manganese, can be used in the construction industry or further processed for metal recovery. Lithium recovery from the slag began in 2017 in collaboration with an external partner. The liquid metal alloy is further refined in hydrometallurgical processes to recover copper, nickel and cobalt by solvent extraction (Thomas et al. 2018).

Accurec recycles cobalt, manganese, nickel and iron while the slag and smoke dust can be treated in additional hydrometallurgical steps for lithium recovery, which is currently not the case due to a lack of economic profit (Thomas et al. 2018).

The recycling process of Recupyl uses mechanical crushing followed by hydrometallurgical treatment. The LIBs are crushed in a housing with defined and controlled atmosphere and pressure. The crushed materials are then filtered into four fractions. Only one fraction, a fine fraction rich in metal oxides and carbon, is further processed. This fraction is sieved to reduce the copper content. The remaining fine powder is further treated in hydrometallurgical steps to obtain solutions of cobalt and lithium salts (Thomas et al. 2018).

The BatRec process is mainly based on a mechanical processing plant. The first step is to crush the batteries in an inert CO₂ atmosphere. Afterwards the crushed batteries are mechanically separated, which leads to a non-ferrous metal-containing metal fraction, a nickel-containing metal fraction, a cobalt and lithium-containing fine fraction and a plastic fraction. The first two metal fractions can be sold to other metal recyclers, while the fine fraction is sold to cobalt and nickel refineries. The plastic fraction can be partially used for energy recovery in a pyrolysis process (Thomas et al. 2018).

So it becomes obvious that most recycling processes focus on the recovery of the valuable cobalt and nickel, while the recycling of lithium or manganese is rather out of scope. Out of an economical perspective, this is reasonable, but this might become a problem when considering the environmental impact: LFP batteries for example contain no economically valuable metals and thus have very low incentive for recycling. Regardless of this the cells still contains aluminium, which has a high greenhouse gas emissions from production and a well-developed recycling chain that is not utilized (Hall and Lutsey 2018).

Romare and Dahllöf compared different potential battery recycling pathways and identified potential net savings of 1–2.5 kg CO₂/kg.

Table 15: LCA results for different recycling stages (Romare and Dahllöf 2017)

Method	g CO ₂ -eq/kg battery	Chemistry
LithoRec (Buchert, et al., 2011b)a) (Prototype scale)	-1035 (hydrometallurgy, see details in Table 23)	35% NMC, 35% NCA and 30% LFP
Libri (Buchert, et al., 2011a) (Prototype scale)	1244 (pyrometallurgy)	35% NMC, 35% NCA and 30% LFP
Umicore (Dunn, et al., 2015) (Industrial scale)	-70% = -1500 g CO ₂ /kg Co	LCO

Hydrometallurgical (Dunn, et al., 2012)	-2000, mainly from removing need for primary Al	LMO
Intermediate physical recycling (Dunn, et al., 2012)	-2000, mainly from removing need for primary Al	LMO
Direct physical recycling (Dunn, et al., 2012)	-2500	LMO

The results of an LCA thereby depends on the chemistries of batteries (high share off NMC or LFP), the recycling process used and therefore the materials regained and also the quality of the final material output (Romare and Dahllöf 2017). Thomas et al. 2018 gives a summary of the results of different LCA studies regarding the role of recycling. They conclude that recycling concepts that are more dependent on energy consumption as e.g. the pyrometallurgical treatment are likely to have higher greenhouse gas emissions, while recycling concepts that are more dependent on the use of solvents as hydrometallurgical treatment, are likely to have higher impacts in other environmental impact categories. In contrast to the operation phase, EoL emissions associated with battery recycling are unlikely to be affected by changes in the electricity mix, as only a small part of the energy input in EoL treatment processes comes from electricity (Thomas et al. 2018).

4.2.5. Environmental impact of li-ion batteries production

This chapter will briefly highlight the environmental impact resulting from the production of battery systems. Romare and Dahllöf 2017 give a summary of the identified greenhouse gas emission given in the reviewed LCA studies¹⁹ for the different life cycle stages. The values for battery grade material production (including raw material mining and refining) are in a range between 48 -121 kg CO₂-e/kWh, while the most likely value might be 60-70 kg CO₂-e/kWh. The manufacturing process of components, cells and battery assembly has a slightly higher environmental impact. The greenhouse gas emissions are thereby in a range between 20-110 CO₂-e/kWh, with a most likely value of 70-110 k CO₂-e/kWh (Romare and Dahllöf 2017). Anyhow, the ranges indicate that there is a high uncertainty regarding the results but the assessment points out that both, the battery grade material production (including raw material mining and refining) as well as the manufacturing have a high impact on greenhouse gas emissions, while the impact of the manufacturing process can be considered as a bit higher.

As already indicated before, also the choice of the cell chemistry has influence on the material consumption and the energy use for processing. Peters and Weil 2018 gives a good summary of the resulting greenhouse gas emission (in GWP). The following Figure 21 gives an overview of the unified (and original) results of this analysis regarding the relative importance of different battery manufacturing components or stages.

¹⁹ Ellingsen et al. 2014; Majeau-Bettez et al. 2011a; Kim et al. 2016; Ambrose und Kendall 2016; Amarakoon et al. 2013

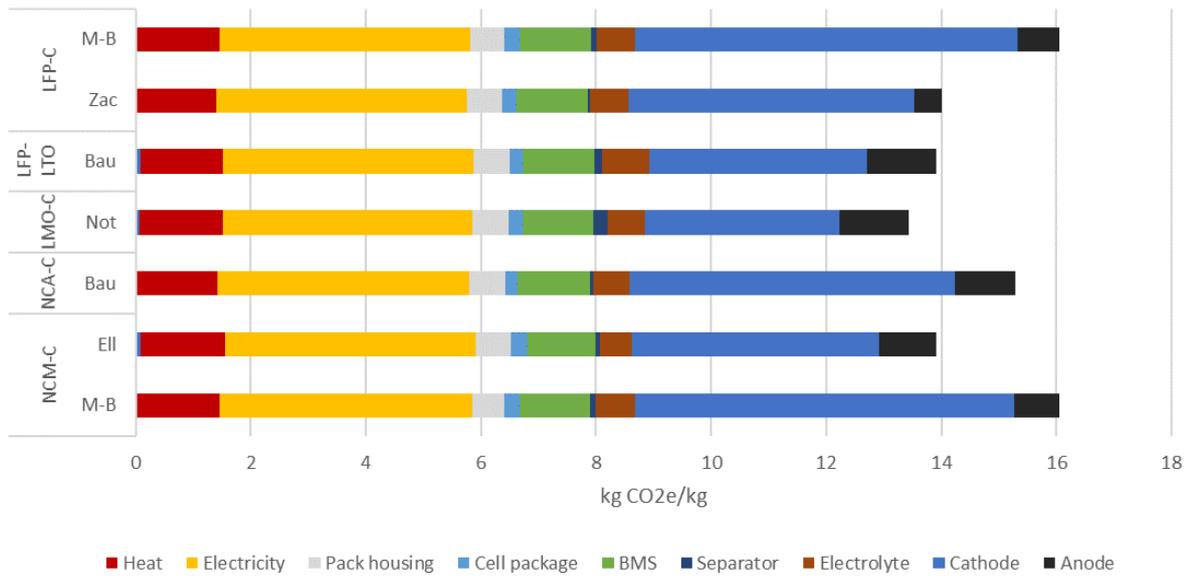


Figure 21: GWP impacts (per kg battery) from the production of Li-ion batteries for different cell chemistries (based on Peters and Weil 2018)

The figure illustrates that especially the cathode materials and the electricity (and heat) have the highest GWP impact. Based on these findings, potential improvements to reduce these emissions focus primarily on a higher energy efficiency in production, the use of low-carbon electricity and the improvement of cell chemicals as well as an increased energy density and battery lifetime (Hill et al. 2018; Romare und Dahllöf 2017; Hall und Lutsey 2018; Peters and Weil 2018).

Hall and Lutsey 2018 state that the energy storage per kilogram of battery, is steadily increasing with an average rate of approximately 5%–8% per year. Although this does not represent an equivalent reduction in materials or energy, they estimate that a 50% increase in battery energy density would lead to a 10%–15% reduction in cumulative energy density. In addition, a longer battery lifetime will lower the initial battery production footprint. As well as the decarbonization of electric grids. Hall and Lutsey 2018 estimate, that a decarbonization of the electric grids around the world (e.g. until 2030) by an average of about 30% will result in approximately 17% lower battery manufacturing emissions by 2030. To quantify the effects of these measures they exemplarily calculated the potential changes in greenhouse gas emissions in g CO₂ e/km in comparison to a reference electric vehicle using this battery in 2017.

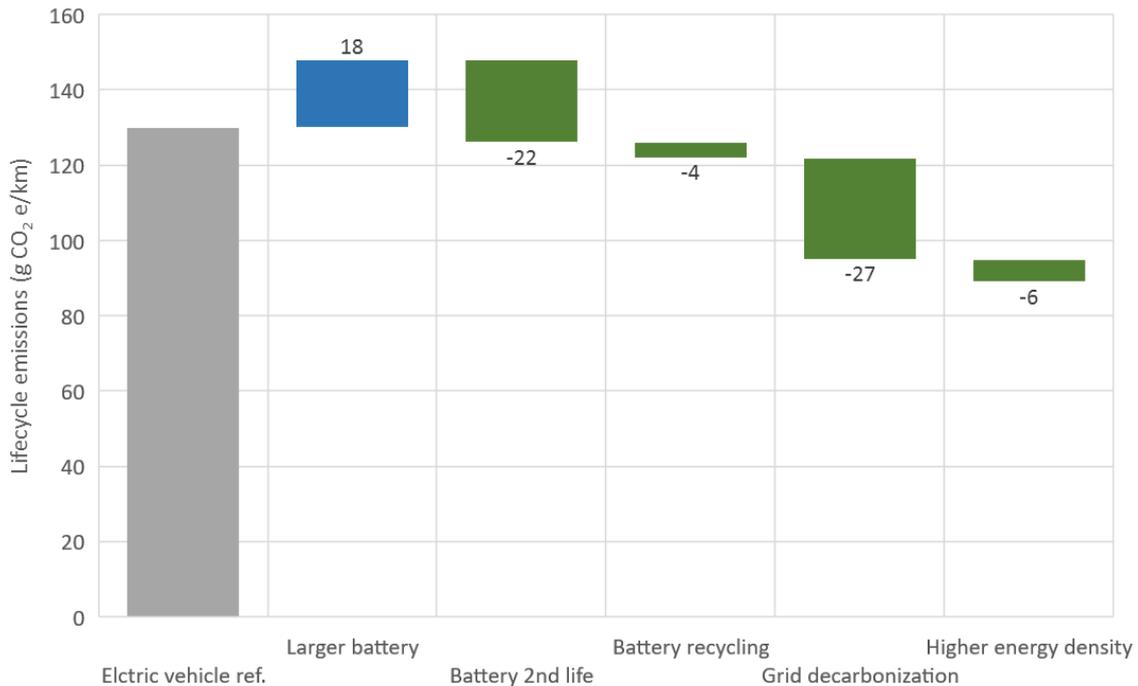


Figure 22: Potential changes in battery greenhouse gas emissions by different measures (Hall and Lutsey 2018)

4.3. Subtask 4.3 - Recommendations

The task 4 report on technologies provides a quite holistic description of the li-ion batteries from a technological point of view as well as over the whole life cycle from the materials sourcing to the end-of-life treatment. Based on the findings in the following some recommendations regarding barriers and opportunities and the following process are listed.

- Due to the rather unsettled market for automotive and stationary li-ion batteries and the great variety of products (cell formats, cell chemistries...) placed on the market a concentration on a "representative cell" is not possible. Thus, for e.g. determining the BOM, an approach based for building a virtual battery is used. The approach allows considering different kind of cells in accordance to their approximate market share and offers a way to deal with this market complexity.
- There is a long list of possible improvement options for li-ion batteries. However, the impact in terms of performance and additional costs, is in the case for most options almost not possible to determine in general way. Thus, extensive investigations would be necessary, considering the specific characteristics of the products and of their intended application. However, in order to be able to make a statement about the effects of improvement options, it is suggested not to consider the improvement options at component level but rather at a higher level. Such an approach seems even more reasonable when looking at different LCA studies which are also rather focusing at this meta-level, e.g.: higher energy density, increased lifetime...).
- Another difference to many other Ecodesign preparatory studies is the possibility of 2nd life applications. This is a quite promising possibility to prolong the service life of a battery and thus to increase the functional unit. This leads to a lower environmental impact per energy service delivered.

- Battery recycling will also play a major role in the future. Anyhow, since this is the specific issue of the Battery directive (which is currently under revision), it makes sense to keep a clear allocation of topics and thus not to consider the subject of recycling any further here, even if some of the technical options may facilitate dismantling and recycling of batteries.

To sum up, the recommendations regarding the scope of the study are to consider the whole battery life cycle, except for recycling which is rather a topic of the Battery directive. Regarding improvement options for a further examination in task 6, the consideration of a prolonged lifetime because of second-life application seems to offer a high potential. Furthermore, the electricity consumed for battery production can have a comparatively high environmental impact and should therefore also be examined close in this preparatory study. Finally, to take account of technological developments, the amount of active and passive materials used to provide a comparative service can be further reduced (also going along with a change in cell chemicals) and should be studied in more depth.

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