ISSN 1831-9424

European Commission

Technical recommendations for the targeted amendment of the European List of Waste entries relevant to batteries

Support for the new batteries regulatory framework - WP8

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2024

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EUR 40087

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JRC139124

EUR 40087

PDF ISBN 978-92-68-21153-3 ISSN 1831-9424 doi:10.2760/7560598 KJ-01-24-092-EN-N

Luxembourg: Publications Office of the European Union, 2024

How to cite this report: European Commission, Joint Research Centre, Egle, L., Pierri, E., García John, E., García-Gutiérrez, P. and Gaudillat, P., *Technical recommendations for the targeted amendment of the European List of Waste entries relevant to batteries*, García John, E. editor(s), Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/7560598, JRC139124.

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Abstract

This report is the deliverable of Work Package 8 Technical support to develop a proposal for the targeted amendment of the European List of Waste entries relevant to batteries of the Joint Research Centre (JRC)'s Administrative Agreement providing support for the new batteries regulatory framework to DG ENV and DG GROW.

The JRC is providing technical support to the accompanying measures related to the Batteries Regulation, in particular for the development of a targeted amendment of the European List of Waste entries relevant to batteries. This potential amendment would help better categorise the waste flows associated with new types of batteries, to improve the accuracy and traceability of battery waste flow monitoring and ensure a level playing field in the EU.

This report presents the results of the technical analysis carried out to support the potential targeted amendment examining batteries, battery wastes, and industry processes; it has been developed through desk research complemented by extensive stakeholder input and field visits.

The report presents current evidence on the relevant battery waste streams identified, their composition and their hazard properties, as well as a recommendation for new or revised six-digit waste code entries to the List of Waste relevant to batteries.

Acknowledgements

The authors would like to acknowledge the support offered by the Waste Expert Group[1] and stakeholders who participated in the workshop and written consultation organised by the JRC. During the stakeholder consultation the Member States Austria, Czech Republic, France, and Sweden provided additional written feedback to the consultation via the Waste Expert Group. The organisations that provided written input via the template or questionnaire are listed below.

Organisations (in alphabetical order):

- BASF
- BLC (The Battery Lifecycle Company GmbH)
- Duesenfeld
- EBRA (European Battery Recycling Association)
- EDI (Euro-Dieuze Industrie)
- Energizer
- EUCOBAT
- EuRIC AISBL
- EUROBAT (Association of European Automotive and Industrial Battery Manufacturers)
- FER (Federación Española de la Recuperación)
- FZSoNic
- Ineris (French National Institute for Industrial Environment and Risks)
- IZA (International Zinc Association)
- Li-Cycle
- Northvolt
- Dr. Marco Ottaviani (Consultant)
- OVAM (Public Waste Agency of Flanders)
- RECHARGE
- SQM Europe
- Tesla
- T & E (Transport & Environment)
- Umicore
- Verkor

Additionally, we thank the colleagues in DG Environment for their support and feedback throughout the project, in particular: Kerstin Lichtenvort, Rana Pant, Daniele Ape, Pauline Wolters, and César Santos Gil, as well as Ewout Deurwaarder from DG Grow (Internal Market, Industry, Entrepreneurship and SMEs). We would like to thank also our JRC colleague Silvia Bobba (JRC.D3), who has provided detailed quantitative data for the forecasts of battery-related waste flows.

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Executive summary

Policy context

The Joint Research Centre (JRC) is providing technical support to the development of targeted amendments to the European List of Waste (LoW) entries relevant to batteries. The amendments are aimed at addressing the evolving battery chemistries, manufacturing and recycling processes, and to foster proper sorting, processing, transport and reporting of waste batteries and associated waste streams. This will increase legal certainty especially regarding hazardous wastes.

This work is developed in the context of the development of a new European legislative framework on batteries centred on the new Batteries and Waste Batteries Regulation (BWBR); it will contribute (in the broader legislative context set by the Waste Framework Directive, Waste Shipment Regulation, REACH/CLP and others) to providing a level playing field in the EU and foster a well-functioning recycling value chain..

Scope and methodology

The report presents the results of the technical analysis supporting the proposed targeted amendment of the List of Waste. Backed by a compilation and assessment of information on material inputs and intermediates of recycling processes for battery-related waste, process description, constituents, and hazardous substances, the analysis includes the identification and survey of relevant battery waste streams, as well as evidence-gathering on the composition and characteristics of these waste streams. The outcome is a formulation of recommendations for classifying the waste streams concerned under new entries in the List of Waste, including a categorisation as hazardous or non-hazardous (or mirror entries).

Key conclusions

- Considering the profound evolution of battery technologies (since the latest revision of the list of waste) and projected expansion of the battery market, a revision of List of Waste codes used to classify waste batteries and related streams is necessary.
- Following the existing structure of the current sub-chapter of the List of Waste concerning waste batteries (16 06) It is proposed that batteries continue to be largely classified according to their dominant chemistry, introducing new codes to reflect current (and potentially future) commercially-relevant chemistries, including lithium-, nickel- and sodium-based.
- Three types of waste have been identified as relevant and corresponding categories are proposed for new LoW entries: waste batteries, battery manufacturing waste, and intermediates of waste battery recycling.
- Most waste battery types are recommended to be classified as hazardous, due to their nature and the presence of one or more hazardous substances in their composition over (or near, taking into account variability) concentrations triggering the assignment of one or several hazard properties.
- Classification of battery-related wastes as hazardous will impact operators in the battery and waste management sectors, which should be supported by accompanying measures at national level and/or through an update of the related legislative framework.

Related and future JRC work

This project is part of a broader support activity from the Joint Research Centre on the development of the new regulatory framework for batteries; the present report is the deliverable of Work Package 8 - *Technical support to develop a proposal for the targeted amendment of the European List of Waste entries relevant to batteries* of the Joint Research Centre (JRC)'s Administrative Agreement providing support for the new batteries regulatory framework to DG ENV and DG GROW.

Within the Administrative Agreement, this project relates to Work Packages analysing end-of-life and circularity aspects of the Battery Regulation, namely Work Package 7 on recycling efficiency and recovery of materials, and Work Package 4 on recycled content obligations for certain elements.

Quick guide

Chapter 1 of the report offers an introduction to the project, including the legislative framework and an overview of current hazard considerations for batteries and waste batteries.

Chapter 2 outlines the scope, including types of waste, and the project methodology including the approach followed for hazard determination.

Chapter 3 reviews the status of waste codes currently applied for battery-related waste, including non-battery specific codes used by operators in the absence of applicable battery-specific codes, as well as national adaptations of the list of waste, in cases where those have emerged.

Chapter 4 is the main technical part of the report and presents the analysis of waste compositions, reviews of the composition for each kind of waste identified, variability in composition and the technical recommendation from JRC based on that evidence to propose a new classification.

Chapter 5 is the summarised output of the work which presents the technical recommendation for new waste codes (new 6-digit code entries in the List of Waste).

Finally, **Chapter 6** presents some conclusions and outlines the next steps which can be informed by this report.

1. Introduction and background

1.1. Background and objectives

1.1.1. Policy context

The Joint Research Centre (JRC) is providing technical support to the preparation, implementation and accompanying measures related to the provisions of the new Batteries and Waste Batteries Regulation (BWBR)[1]. In particular, as announced in the Proposal for a Batteries Regulation[2], the JRC will support the development of targeted amendments of the European List of Waste (LoW) entries relevant to batteries.

The European List of Waste (Commission Decision 2000/532/EC[3], last amended by Decision 2014/955/EU), in its current formulation already contains a number of entries for batteries and for electrolyte separately collected from batteries in the sub-chapter 16 06 "Batteries and accumulators[4]"[5] and sub-chapter 20 01 "separately collected fractions (of municipal waste and similar commercial and industrial waste)"[6]; see additional analysis in section 2.

In the context of the new Batteries Regulation and the communication on Critical Raw Materials[7], a targeted amendment of the List of Waste is envisaged to take place in 2024 to take account of the existing battery (alkaline-based, zinc-based) chemistries and emergence of new battery chemistries (in particular lithium-based[8] and nickel-based[9] batteries), evolving manufacturing and recycling processes, and proper sorting, recycling and reporting of waste batteries. The objective is to improve the identification and classification of relevant waste streams arising from the manufacturing of batteries (e.g. cut-offs[10] and waste containing cathode and anode materials) and from their recycling (e.g. black mass).

This proposed amendment should contribute to the identification and statistical monitoring and traceability of the different waste streams and increase legal certainty on the status of the different waste batteries and process wastes as hazardous / non-hazardous waste. An important aim is the creation of a fair, level playing field for existing and future recycling operators as well as actors in the broader value chain, e.g. in logistics. This work also aims more broadly to foster the setup of a well-functioning recycling value chain, supporting the application of rules on recycling efficiencies for batteries[11] and on recycled content in new batteries.[12].

This report presents the results of the technical analysis carried out to support the proposed targeted amendment of the List of Waste. The work was based on several work strands including:

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[1] Regulation (EU) 2023/1542. See in particular Recital 116 "[Commission Decision 2000/532/EC] should be revised to reflect all battery chemistries, in particular the codes for lithium-based waste batteries, in order to enable proper sorting and reporting of such waste batteries".

[2] COM (2020) 798 final, p. 14

[3] 2000/532/EC: Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste

[4] Note that the terminology predates the adoption of the BWBR which amended the definition of batteries and removed the use of the term 'accumulator' (now included in the broader definition of batteries). This is reflected throughout the report, where mentions of 'batteries and accumulators' only refer to the former nomenclature, and wherever possible, the new or recommended nomenclature aligns with the BWBR.

[5] current entries: 16 06 01* Lead batteries; 16 06 02* Ni-Cd batteries; 16 06 03* mercury-containing batteries; 16 06 04 alkaline batteries (except 16 06 03); 16 06 05 other batteries and accumulators; 16 06 06 separately collected electrolyte from batteries and accumulators (*the asterisk indicates the waste is classified as hazardous waste).

[6] 20 01 33* batteries and accumulators included in 16 06 01, 16 06 02 or 16 06 03 and unsorted batteries and accumulators containing these batteries; 20 01 34 batteries and accumulators other than those mentioned in 20 01 33.

[7] COM (2023) 165, the Communication on a secure and sustainable supply of critical raw materials in support of the twin transitions, states that "The Commission will propose in 2024 the inclusion of waste codes for Lithium-ion batteries and intermediate waste streams ("black masses") under the European List of Waste to ensure their proper recycling within the EU".

[8] Examples for Li-based batteries: NMC (Nickel manganese cobalt lithium batteries), LFP (lithium iron phosphate batteries)

[9] Examples for Ni-based batteries: NiMH (nickel-metal hydride batteries), Na–$NiCl_2$ (sodium-nickel chloride batteries)

[10] whenever those become waste, and are not for instance reused in the same manufacturing process.

[11] rules for the calculation, verification and reporting of recycling efficiencies for lead-acid batteries, lithium-based batteries, nickel-cadmium batteries and other waste batteries in the delegated act envisaged under Article 57(4) of the new Batteries Regulation

[12] rules on the declaration, and incorporation of minimum content, of recycled materials (lead, nickel, cobalt, lithium) in some battery types in an implementing act envisaged under Article 8 of the new Batteries Regulation.

- a survey of relevant battery waste streams to cover all major batteries chemistries, or fractions thereof, with a special focus on the different types of lithium- and nickel-based batteries;
- identification of battery-relevant waste streams currently classified in the LoW that may require reassessment in order to adapt to technical progress and support the objectives of the new Batteries Regulation, in particular regarding recycling and shipment of waste batteries;
- evidence-gathering of composition as well as physicochemical and toxicological characteristics of the identified waste streams, with particular attention to substances that are classified or that meet the criteria for classification as hazardous under the CLP Regulation (EC 1272/2008); and an estimation of the variability in the composition of the relevant waste streams (relevant to decide upon the possible need for a mirror entry);
- formulation of recommendations to classify the waste streams concerned as hazardous / non-hazardous including a justification of the applicable hazard properties according to Annex III of Directive 2008/98/EC and taking into account the Annex of Decision 2000/532/EC; formulation of recommendations for new or revised entries in the List of Waste, with a view to clarifying the classification as absolute hazardous or non-hazardous waste of existing and new entries, or introducing mirror entries.

The above tasks are supported, for the relevant waste streams, by a compilation and assessment of information on material inputs to corresponding waste batteries recycling processes, process description, list of relevant constituents and composition of the waste (focus on major constituents and hazardous substances) and information on the classification or self-classifications of relevant substances.

1.1.2. Objective of the work

The deliverable of this work is the present technical report providing evidence to support a potential targeted amendment of the List of Waste for entries relevant to batteries.

Whilst the recommendations in this report will inform the preparation of an act to amend the List of Waste, the outcome of the subsequent decision-making process is not bound by the conclusions of the present work, which is not an authoritative interpretation of legislation nor does it represent a commitment by the European Commission to follow the recommendations arising from this work.

1.2. Legislative framework

1.2.1. Legal definition of waste and waste batteries

In Article 3 (1) of Directive 2008/98/EC (Waste Framework Directive (WFD)) **waste** is defined as *"any substance or object which the holder discards or intends or is required to discard*".

As per Article 7 (1) of the Waste Framework Directive on the List of Waste: "the inclusion of a substance or object in the list shall not mean that it is waste in all circumstances. A substance or object shall be considered to be waste only where the definition in point (1) of Article 3 is met".

In Article 3 (50) of the Battery Regulation, a **waste battery** is defined as *"any battery*[13] *which is waste as defined in Article 3, point (1), of Directive 2008/98/EC"* and **battery manufacturing waste** is defined in Article 3(51) as *"the materials or objects rejected during the battery manufacturing process, which cannot be re-used as an integral part in the same process and need to be recycled".*

[13] as per Article 3.1. (1) of the Battery Regulation: 'battery' means any device delivering electrical energy generated by direct conversion of chemical energy, having internal or external storage, and consisting of one or more non-rechargeable or rechargeable battery cells, modules or of packs of them, and includes a battery that has been subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing.

1.2.2. Status of intermediate and output fractions of waste battery recycling

The determination of the status of intermediate and output fractions of waste battery recycling as waste / non-waste is not always trivial; this work does not attempt to establish the waste or non-waste status of specific fractions arising from batteries. It should be noted that, as indicated in Article 7(1) of the Waste Framework Directive, "The inclusion of a substance or object in the list shall not mean that it is waste in all circumstances. A substance or object shall be considered to be waste only where the definition in point (1) of Article 3 is met[14]".

Waste batteries that are treated in a waste management operation remain waste until end-of-waste status is reached.

A battery fraction resulting from manufacturing that does not fulfil by-product criteria defined in Article 5 of the WFD, may qualify for end-of-waste status if it complies with the conditions laid down in Article 6 of the WFD on end-of-waste status. Considering that no EU-wide end-of-waste criteria are in place for batteries or fractions thereof, it may be possible for recyclers of waste batteries to obtain end-of-waste recognition for specific output fractions from national authorities, be it via national EoW criteria or via case by case decisions, as established in Articles 6(3) and 6(4) of the WFD.

Once the material is placed on the market for the first time after end-of-waste status has been reached, it should comply with all relevant requirements applicable to products (Article 6 (5) of the WFD).

1.2.3. Shipment of waste and waste batteries

As regards their shipment, there is a clear distinction between *used batteries* and *waste batteries*. As per Article 72 (1) of the Battery Regulation, **shipment of waste batteries** or fractions thereof should be in compliance with Regulation (EC) 1013/2006 (Waste Shipment Regulation (WSR)) and Commission Regulation (EC) No 1418/2007.

Shipment of used batteries should follow minimum requirements laid down in Annex XIV of the Batteries Regulation, including testing of the state of health and the presence of hazardous substances, to demonstrate that the load does not consist of waste batteries.

In addition, the transport of battery cells, batteries, and equipment containing batteries is regulated by UN, regional, and national legislation. Among others, the transport of batteries within and outside the EU is regulated by the United Nations Economic Commission for Europe (UNECE) and other mode-specific transport conventions and authorities such as ICAO (air), IMO (+IMDG, sea), RID (rail) and ADR (road).

1.2.4. European List of Waste (current List of Waste and waste codes)

The **European List of Waste** (Commission Decision 2000/532/EC[2], last amended by Decision 2014/955/EU) provides common terminology for classifying waste across the EU. This helps manage waste, including hazardous waste. Codes are assigned in a broad variety of activities, including the transport of waste, installations' permits (which often refer also to specific waste codes), or as a basis for waste statistics. The LoW provides a harmonised list for coding all waste.

A technical **guidance document on the classification of waste**[15] was issued by the Commission to help national authorities, local authorities, and businesses (e.g. for permitting issues) to correctly interpret and apply EU law on the classification of waste. It provides a comprehensive overview of relevant EU law, examples of waste types for which classification is considered difficult by stakeholders, and step-by-step information on how to assess whether waste displays hazardous properties and on how to classify it.

[14] see 1.2.1 above. §1.

[15] Commission notice on technical guidance on the classification of waste (2018/C 124/01)

The List of Waste (LoW) classifies waste entries according to the hazard properties of waste. Waste can be categorised into 'Absolute hazardous entries (AH)', 'absolute non-hazardous entries (ANH)' and 'mirror entries (MH/MNH)' (**Figure 1**).

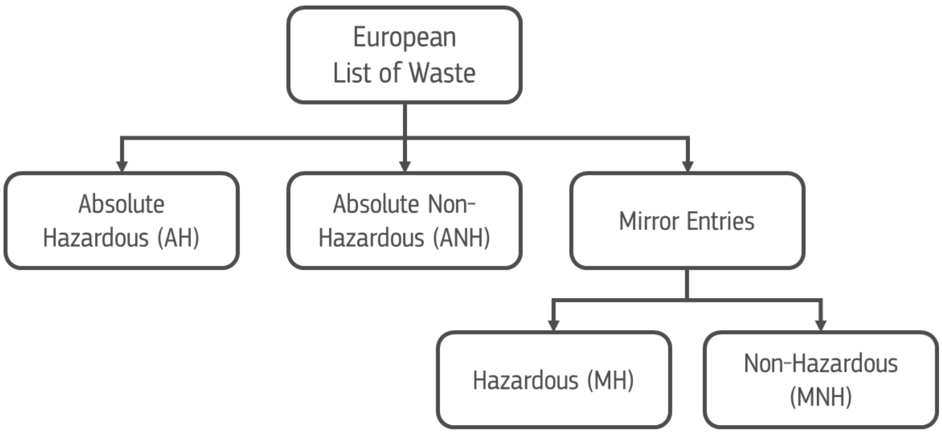
Wastes assigned to **absolute hazardous** entries are considered hazardous without any further assessment[16] and the entry is marked with an asterisk (*). Although no further assessment is necessary to classify the waste, it may still be necessary to assess *which* hazardous properties the waste displays, if required for the fulfilment of correct labelling of hazardous waste.

Wastes assigned to absolute **non-hazardous entries** are considered non-hazardous without any further assessment[17].

In numerous cases, waste from the same source might, under the LoW be allocated **to a hazardous entry (MH) or to a non-hazardous entry (MNH)** depending on the specific characteristics and on the composition of the waste. In this case, "mirror entries" are defined: further assessment is required to determine whether the waste is to be assigned the hazardous mirror entry, or the non-hazardous mirror entry.

The methodology to determine if waste is hazardous or non-hazardous is detailed in section 2.1.4.6.

Figure 1. Categories of entries in the EU List of Waste



Specific waste codes for waste from used batteries are currently listed in 16.06 and 20.01 of the European List of Waste (LoW) (EC, 2000). The following **Table 1** provides the specific waste codes related to batteries and shows for instance, that lithium- or nickel-based batteries (other than Ni-Cd) can currently be assigned to the waste codes 16 06 05 or 20 01 34 which are absolute non-hazardous codes.

Table 1. Current waste codes for batteries according to the European List of Waste

Code	**Description**	**Category**
16 06 01*	Lead batteries	AH
16 06 02*	Ni-Cd batteries	AH
16 06 03*	Mercury- containing batteries	AH
16 06 04	Alkaline batteries (except 16 06 03*)	ANH

[16] According to Art. 7 (3) of the WFD, "Where a Member State has evidence to show that specific waste that appears on the list as hazardous waste does not display any of the properties listed in Annex III, it may consider that waste as non- hazardous waste.", e.g. by demonstrating it does not display any of the hazardous properties HP1–HP15 and/or contain Persistent Organic Pollutants (POPs)

[17] According to Art. 7 (2) of the WFD, "A Member State may consider waste as hazardous waste where, even though it does not appear as such on the list of waste, it displays one or more of the properties listed in Annex III."

16 06 05	Other batteries and accumulators	ANH
16 06 06*	Separately collected electrolyte from batteries and accumulators	AH
20 01 33*	Batteries and accumulators included in 16 06 01*, 16 06 02* or 16 06 03* and unsorted batteries and accumulators containing these batteries	MH
20 01 34	Batteries and accumulators other than those mentioned in 20 01 33*	MNH

Chapter 20 includes municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions. If separate codes are created for new types of batteries (e.g. Li- or Ni- based), they should be also reflected in this chapter. However, as chapter 20 relates to municipal waste, industrial wastes or waste from vehicles cannot be addressed in this chapter.

Batteries are also part of waste electrical and electronic equipment (WEEE) and lithium-based batteries are an essential component of vehicles and remain therein upon these becoming end-of-life vehicles (ELVs). Light means of transport (LMT) including batteries such as e-bikes and electric scooters are within the scope of the WEEE Directive. In case the batteries are separated from the WEEE or ELV, the batteries could be associated to the non-specific waste code **16 02 15*** (hazardous components removed from discarded equipment; for WEEE) or to waste code **16 01 21*** (hazardous components other than those mentioned in 16 01 07 to 16 01 11 and 16 01 13 and 16 01 14; for ELV). However, after an extraction, the batteries fall under the Battery Regulation and shall be assigned to a battery waste code (**sub-chapter 16 06**).

1.2.5. Shipment of batteries (as products)

In this section, unless otherwise specified, codes and classifications refer to the **UN framework** for the classification and transport of dangerous goods (UN Model Regulations on the Transport of Dangerous Goods - TDG).

1.2.5.1. *Lithium-based batteries*

Lithium-based batteries are dangerous goods and must be transported as such; they are associated to class 9 (miscellaneous dangerous substances and articles).

Class 9 covers substances and articles which, during carriage, present a danger not covered by the heading of other classes. This implies that all shipments of such goods are required to carry the specific label for this class. A specific label within class 9 (Class 9A - Lithium-based batteries) has been developed (see opposite, with an additional mention of the UN number, detailed below). Potential risks from lithium-based batteries are **risk of short-circuit and fire, risk of injury from direct current, and chemical substance risk on the human body** (e.g. exposure of chemical substances to eye, skin, lungs but also toxic gas (hydrogen fluoride)).

Figure 2. Class 9A Lithium-based battery label

To ensure transport safety, Lithium-based batteries are divided into the two main categories, 'lithium metal' (formerly mostly non-rechargeable or disposable batteries, i.e. primary batteries); and 'lithium ion' (rechargeable batteries).

A second distinction takes into account the type of packaging with which they will be shipped (battery alone, battery with a device – e.g. car, vehicle or generic device – and, inserted inside the device itself) – see IATA (2020).

Cells and batteries contained in equipment, or cells and batteries packed with equipment, containing lithium in any form should be assigned to the following hazardous UN identification numbers:

Non-rechargeable or disposable lithium-based batteries

— **UN 3090**: Lithium metal batteries (including lithium alloy batteries)

— **UN 3091**: Lithium metal batteries contained in equipment or lithium metal batteries packed with equipment (including lithium alloy batteries)

Rechargeable lithium-based batteries

— **UN 3480**: Lithium-ion batteries (including lithium ion polymer batteries)

— **UN 3481**: Lithium-ion batteries contained in equipment[18] or lithium-ion batteries packed with equipment [19] (including lithium ion polymer batteries)

Figure 3. UN framework lithium-based battery marks

Lithium-based batteries in containers (rechargeable or non-rechargeable)

— **UN 3536**: Lithium-based batteries installed in cargo transport unit (lithium ion batteries or lithium metal batteries)

Vehicles

— **UN 3556**: Vehicle, Lithium Ion Battery Powered

— **UN 3557**: Vehicle, Lithium Metal Battery Powered

All types of lithium-based batteries are considered to be dangerous goods for the purposes of transport by the UN classification. Even though certain types of lithium-based batteries such as lithium iron phosphate ($LiFePO_4$) are considered in some commercial applications to be safer, as they have a lower risk of explosion or combustion, they can store considerable amounts of energy and its release can result in significant electric shock hazard (HSE, 2024).

1.2.5.2. *Shipment of other batteries and electrolytes for batteries*

Other batteries based on lead, Ni-Cd, NiMH, and $Na\text{-}NiCl_2$ are classified as “Class 4.3 (substances which, in contact with water, emit flammable gases)”, “Class 8 (corrosive substances)” and “Class 9 (miscellaneous dangerous substances and articles)” dangerous goods in accordance with the UN framework for the transport of dangerous goods.

ADR entries for other (non-lithium) batteries are:

— **UN 2794**: Batteries, wet, filled with acid, electric storage (class 8)

— **UN 2795**: Batteries, wet, filled with alkali, electric storage (class 8)

— **UN 2796**: Battery fluid, acid (class 8)

— **UN 2797**: Battery fluid, alkali (class 8)

— **UN 2800**: Batteries wet, non-spillable, electric storage (class 8)

— **UN 3028**: Batteries dry, containing potassium hydroxide solid, electric storage (class 8)

— **UN 3171**: Battery powered vehicle or equipment (class 9)

— **UN 3292**: Batteries containing sodium[20] (class 4.3)

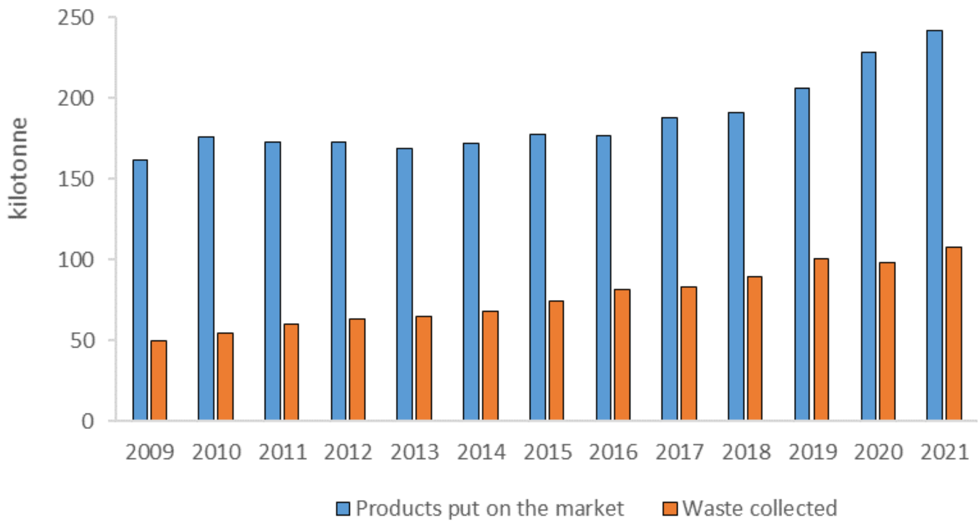
[18] e.g. computer, smartphone, etc… NB vehicles have their own UN number (UN 3171, see below)
[19] e.g. electric tool, radio control equipment, etc.
[20] full denomination “Batteries, containing metallic sodium or sodium alloy, or cells, containing metallic sodium or sodium alloy”

— **UN 3496**: Batteries, nickel-metal hydride (class 9), not subject to ADR
— **UN 3551**: Sodium Ion Batteries with organic electrolyte
— **UN 3552**: Sodium Ion Batteries contained in equipment or Sodium Ion Batteries packed with equipment, with organic electrolyte
— **UN 3558**: Vehicle, Sodium-Ion-battery powered.

1.3. Market perspective

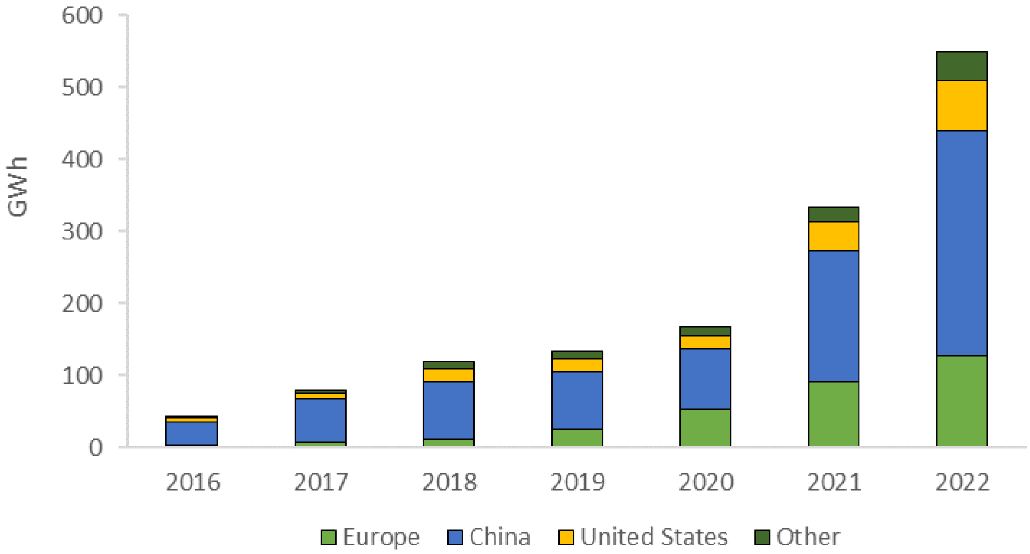
In the EU, around 242 kilotonnes (kt) of portable batteries and accumulators were put on the market in 2021, according to EUROSTAT (see Figure 4). Approximately 108 kt of used portable batteries and accumulators were collected as recyclable waste in the same year, which corresponds to ca. 48 % of the average annual sales of portable batteries calculated in the period 2018–2021.

Figure 4. Sales and collection of portable batteries in the EU-27 in the period 2009–2021 (EUROSTAT, 2023).



As the demand for electric vehicles (EV) increases globally, battery production has also increased in recent years, with over 500 GWh per year of factory capacity expected to be installed globally by 2030 (McKinsey & Company (2023)). Figure 5 depicts the automotive lithium-based battery demand by world region from 2016 to 2022.

Figure 5. Automotive lithium-based battery demand by world region, 2016–2022; adapted from IEA (2023)



As a result of the electrification of the transport sector, there will be a significant growth in battery waste in the coming years, with around 350 kt of such waste projected to be produced annually in 2030 (27.1 % compound annual growth rate from 2021), as shown in Figure 6. As presented in Figure 7, another study forecasts even greater amounts of battery manufacturing waste and end of life batteries in 2030 (~750 kt/yr)

According to McKinsey & Company (2023), cell manufacturing waste can be as high as 30 % of the total cell production when a new battery plant is launched, resulting in a significant source of battery waste arising from markets where EV battery manufacturing is developing. Consequently, battery manufacturing waste is expected to remain the primary source of battery waste until around 2030. From 2030, end-of-life EV batteries are expected to represent the majority of the total battery waste (Umicore, personal communication, 22 December 2023; Avicenne Energy (2023)).

Figure 6. Development and forecast for End-of-life EV batteries and battery manufacturing waste until 2030

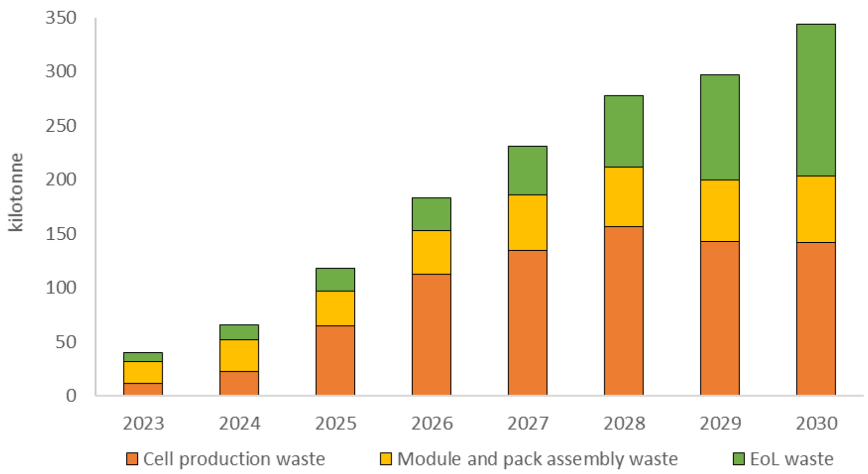
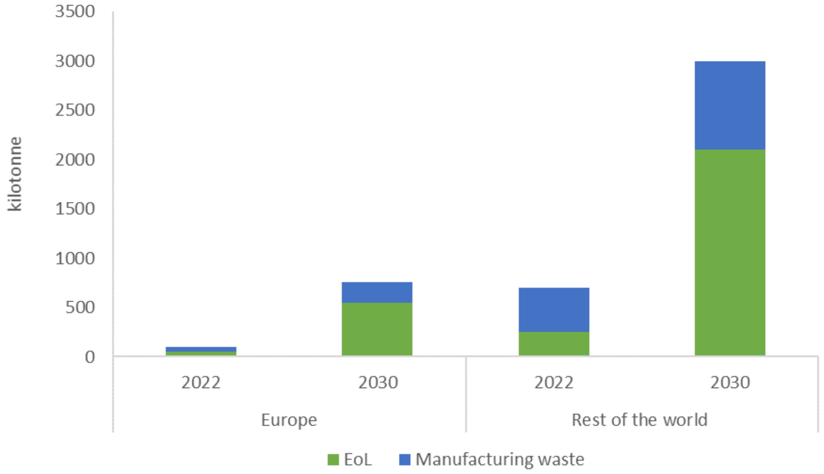


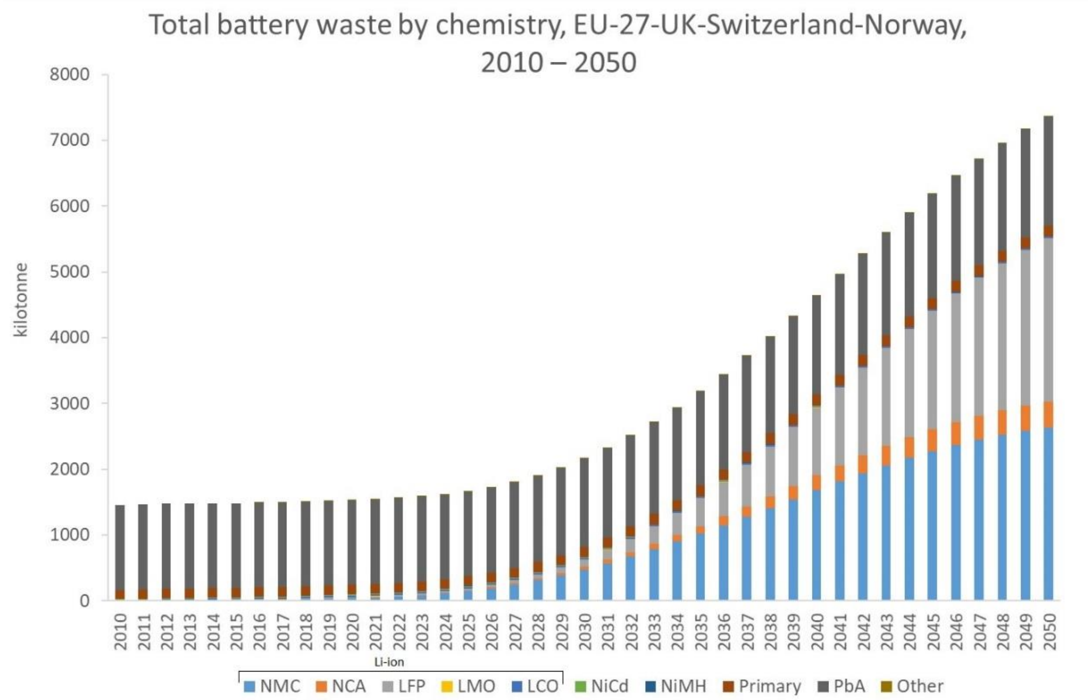
Figure 7. Waste lithium-based batteries available for recycling, 2022 and 2030 (adapted from Avicenne Energy (2023))



Besides lithium-based batteries, the market for sodium-based batteries (including SIB:sodium ion batteries) is also expected to grow in the near future. However, the current forecasts are highly uncertain as the following sources show. Wood Mackenzie (2023) forecasts just under 40 GWh of Na-ion global cell production capacity by 2030, whereas (Siddiqi and Holland, 2023) forecast around 10 GWh by 2025 and just under 70 GWh in 2033. A more ambitious projection is made by Zhao et al. (2023), who argue that the demand for SIBs will grow from 12 GWh in 2023 to 400–500 GWh by 2030, representing more than 20 % of the global battery market.

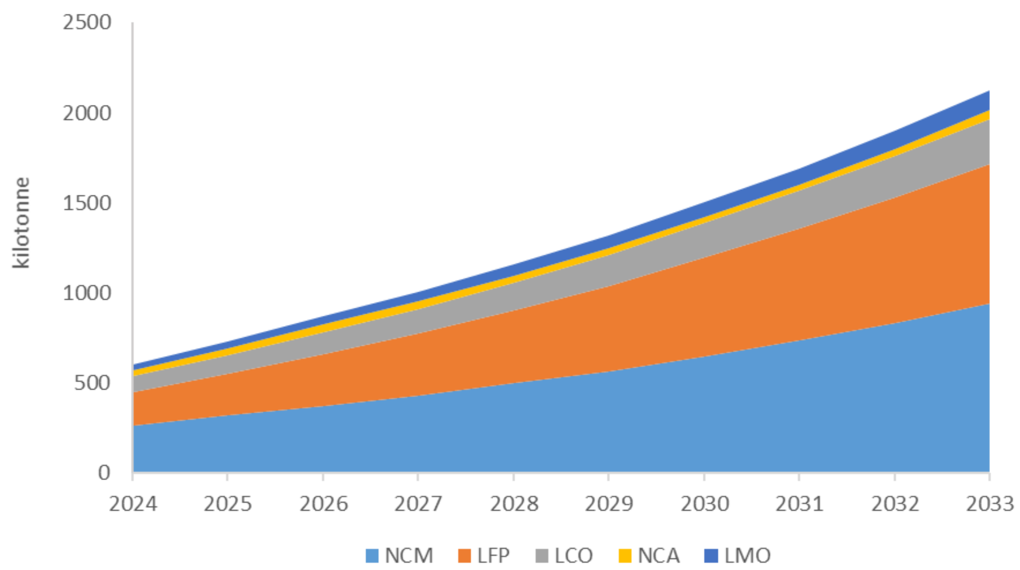
Figure 8 shows the amount of waste batteries projected to be generated over the period 2010–2050, broken down by chemistry, estimated by the JRC battery model (Huisman and Bobba, 2021). Note that the model predicts significant growth of battery waste available for collection and recycling from 2030, especially from the NMC and LFP types, as more end-of-life EV batteries become available.

Figure 8. Total weight of battery waste generated in the EU-27, UK, Switzerland and Norway, 2010–2050 grouped by battery chemistry (NMC: nickel manganese cobalt; NCA: nickel cobalt aluminium; LFP: lithium iron phosphate; LMO: lithium manganese oxide; LCO: lithium cobalt oxide; NiCd: nickel–cadmium; NiMH: nickel–metal hydride; Primary: non-rechargeable (alkaline, Zinc-, Silver- and Lithium-based portable batteries); PbA: lead-acid). Source: Huisman and Bobba, 2021.



A similar trend is observed in the production of black mass (Figure 9), which is expected to grow from ca. 500 kt in 2024 to ca. 2,000 kt in 2033, according to Fastmarkets (2023).

Figure 9. Global Lithium-based batteries black mass production forecast by chemistry. NMC: nickel manganese cobalt; LFP: lithium iron phosphate; LCO: lithium cobalt oxide; NCA: nickel cobalt aluminium; LMO: lithium manganese oxide. Source Fastmarkets, 2023



In light of the data presented in this section, significant volumes of waste batteries as categorised by the present work will be generated in the coming decades, with an increase in overall volume of an order of magnitude (ca. 1,500 kt waste batteries handled in 2010 vs 8,000 kt projected beyond 2050). This highlights the need for increased clarity in waste categorisation as well as the importance of accurate statistics on generated waste volumes. By 2035 it is envisaged that waste lithium-based battery will represent ca. 50 % of all battery waste generated in the EU, while by 2040 this is projected to be as high as 75 %, and increasing. These figures are expected to correlate with the relative amounts of the different black mass chemistries.

2. Scope and methodology (status, waste streams, hazard determination)

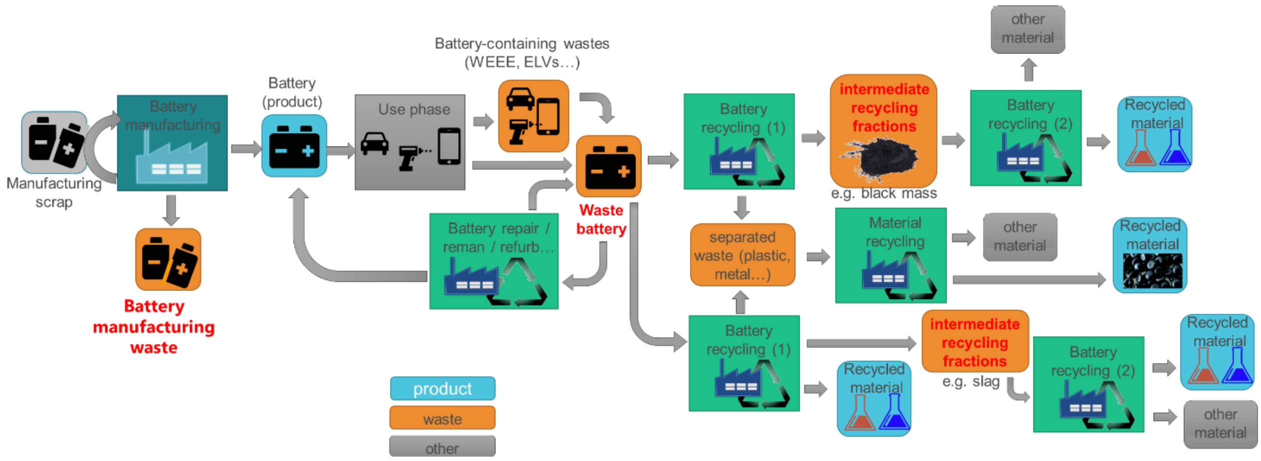
In this chapter, the scope of this work carried out is defined, as well as the methodology used to classify the different types of battery waste.

2.1. Scope

2.1.1. Mapping battery-related waste streams

The first step is the identification of the relevant wastes that arise along the whole battery process chain. A simplified diagram of the value chain (for all battery types) is represented below.

Figure 10. Schematic battery and waste battery lifecycle



N.B. the simplified flows above do not purport to represent accurately or exhaustively any specific battery lifecycle; nor are the material classifications or categorisations authoritative.

Further consideration is given to individual waste streams in the rest of the document.

In this work, the following battery related waste streams are considered in the scope:

— Battery manufacturing waste;

— Waste batteries;

— Intermediate material flows of battery waste treatment.

These are examined in more detail in the three sections below, in particular according to the different battery types (chemistries).

2.1.2. Battery manufacturing waste

Battery manufacturing waste is defined in Article 3 (51) of the Battery Regulation as “the materials or objects rejected during the battery manufacturing process, which cannot be re-used as an integral part in the same process and need to be recycled”.

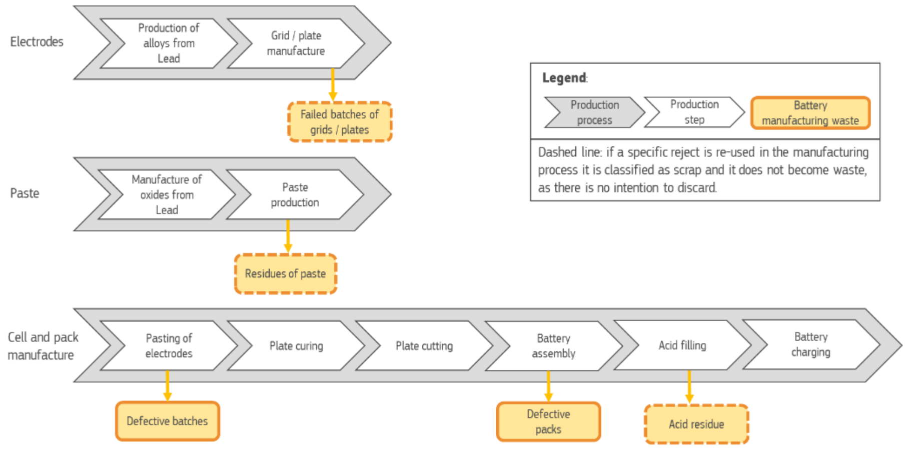
In the following, the manufacturing processes of the battery chemistries in scope are briefly described. Waste occurring along the manufacturing process can vary depending on the process itself, the battery format and the chemistry.

2.1.2.1. Lead-acid battery manufacturing waste

Lead-acid batteries are one of the oldest and most widely used types of rechargeable batteries. They are commonly used in vehicles, uninterruptible power supplies, and various other applications. The manufacturing process of lead-acid batteries is well-established and involves several key steps, including the production of lead oxide, the formation of battery plates, the assembly of the battery cells, and the final filling and sealing of the battery case.

Lead battery manufacturing is often linked to larger-scale operations including lead smelting; in that case, most of the lead-containing rejects are fed back into the lead-processing operation.

Figure 11. Simplified flow-chart of the lead-acid battery manufacturing process and related battery manufacturing waste



Source: based on (ILO, 2011)

2.1.2.2. Lithium-based battery manufacturing waste

The lithium-based battery manufacturing process can be divided in different sub-processes from the synthesis of active materials for electrode production up to the assembly of the battery pack (**Figure 12**). Possible rejects that can be generated in **electrode production** are residues of active materials, solvents, binder, additives (in the mixing process) and electrode cut-offs (in the slitting process). Failed batches of slurry and electrodes could also be generated.

In the **separator production** film cut-offs can be generated.

Typical rejects of the **battery cell production** are residues of electrolyte (in the electrolyte filling process) and defective cells (after testing).

When assembling cells in the **battery module production** process, defective cells can be detected and discarded. Modules that do not fulfil the given quality requirements can also be disposed of by the manufacturer.

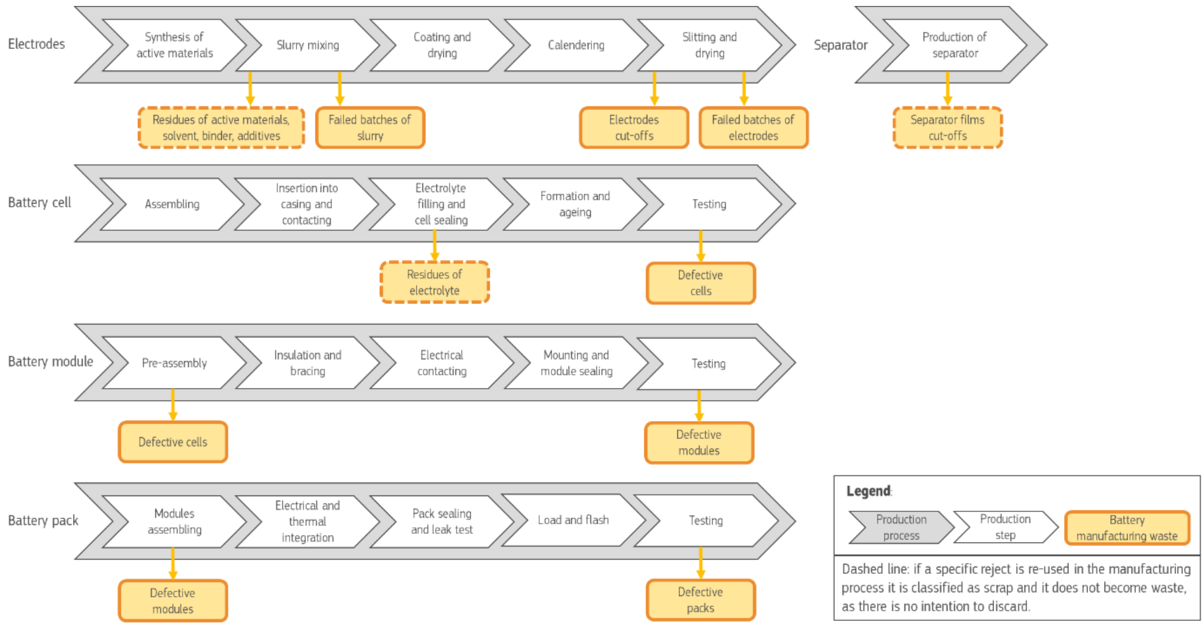
Finally, in the **battery pack production** process, defective modules can be identified during assembly and defective packs can be identified during the final testing.

Hence waste streams from lithium-based battery manufacturing can include:

- Residues of active materials, solvent, binder, and additives
- Failed batches of slurry (NB not applicable in the case of dry cell manufacturing)
- Electrode cut-offs and failed batches of electrodes
- Separator film cut-offs
- Residues of electrolyte
- Defective cells, modules and packs.

It is to be noted that the classification of a substance or an object as waste depends upon the *intention or obligation of the manufacturer to discard* the specific reject (WFD, art 3(1)). Rejects that are re-used in the manufacturing process do not become waste. Those streams are referred to as “battery manufacturing scrap”.

Figure 12. Simplified flow-chart of the lithium-based battery manufacturing process and the related battery manufacturing waste



Source: based on (Liu et al., 2021; VDMA, 2023)

2.1.2.3. Nickel-based battery manufacturing waste

In analogy with lithium-based batteries, the manufacturing process of **NiMH batteries** can be divided in four main sub-processes: production of electrodes, assembling of the cell, module and pack (see **Figure 13**).

Possible rejects generated in the first step are residues active materials, binder and additives (in the mixing process), failed batches of paste, as well as cut-offs and failed batches of electrodes.

Rejects of the cell production step are residues of electrolyte (in the electrolyte filling process) and defective cells (after testing).

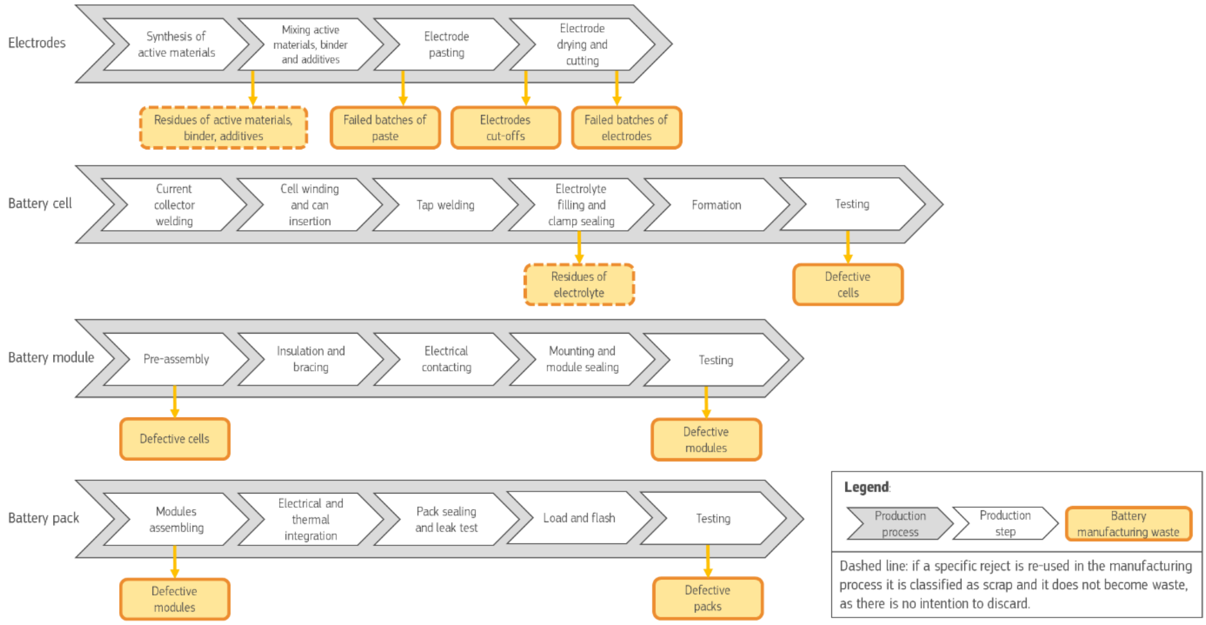
In the module assembly defective cells can also be detected. Modules that do not fulfil the given quality requirements can also be disposed of.

In the pack assembly, defective modules can be identified; during the final testing, defective packs can be discarded of.

Waste streams from NiMH battery manufacturing can include:

- Residues of active materials, binder, and additives
- Failed batches of electrode paste
- Electrode cut-offs and failed batches of electrodes
- Residues of electrolyte
- Defective cells, modules and packs.

Figure 13. Simplified flow-chart of NiMH battery manufacturing process and the related battery manufacturing waste



Source: based on (Young et al., 2017)

The production process of **Na-NiCl₂** batteries consists of three main steps: electrode production, cell assembly and pack assembly (see **Figure 14**).

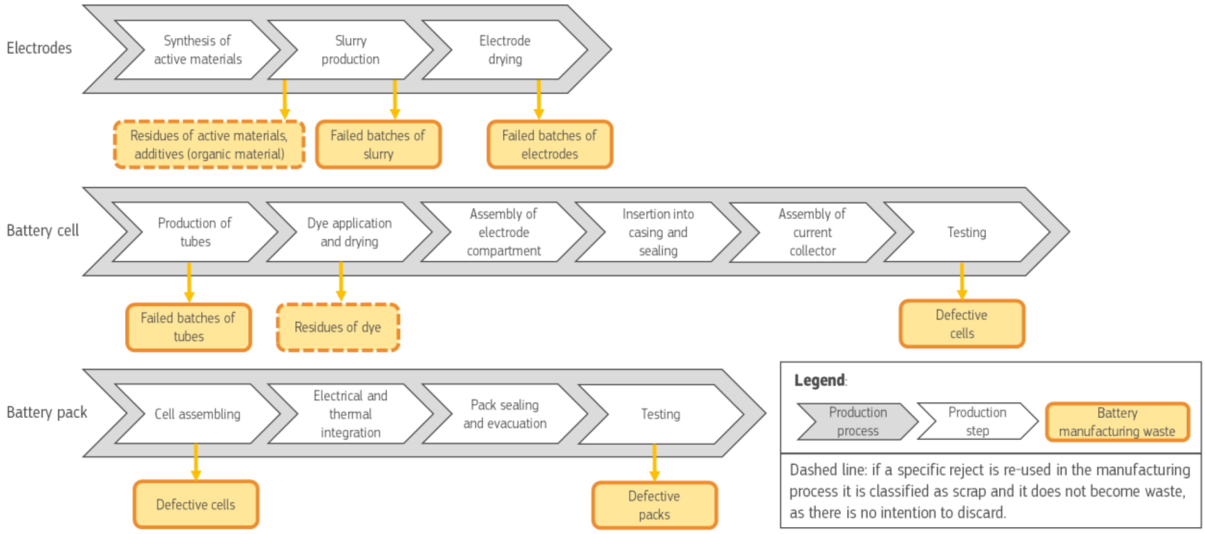
Rejects that can occur in the electrode production are residues of active material and additives (organic material), as well as failed batches of slurry and of electrodes.

During the tubes production and dye application, failed batches of tubes and residues of dye can occur, respectively. Defective cells can be detected during the testing process as well as during the pack assembly (cells are assembled directly into battery packs). Packs not fulfilling the technical requirements can be discarded of at the end of the production process.

Waste streams from $Na\text{-}NiCl_2$ battery manufacturing can include:

- Residues of active materials and additives
- Failed batches of slurry and electrodes
- Failed batches of tubes and residues of dye
- Defective cells and packs.

Figure 14. Simplified flow-chart of Na-NiCl$_2$ battery manufacturing process and the related battery manufacturing waste



Source: based on (Sudworth, 2001)

2.1.2.4. Alkaline-based battery manufacturing waste

The production of alkaline-based battery cells can be divided in three sub-processes: production of cathode, production of anode and cell assembly (see **Figure 15**).

To produce the cathode, manganese dioxide powder is mixed with graphite and water, forming a paste, which is coated with a graphite substrate. In this step, residues of MnO_2 and graphite can occur, as well as failed batches of paste and cathode.

The anode is made of zinc powder mixed with a gelling agent to obtain a paste. The paste is compressed into anode pellets that are sintered at high temperatures to ensure binding. At this stage, residues of Zn powder and gelling agents can occur. Typical rejects are failed batches of the anode paste and anode pellets.

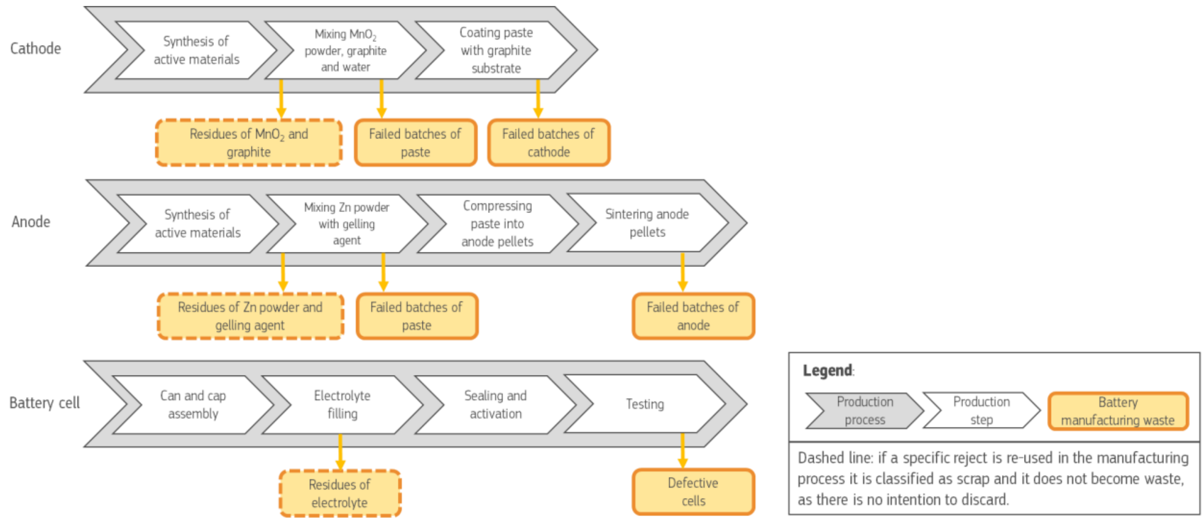
The battery can (steel) is formed into a cylindrical shape. The cap, made of nickel-plated steel, includes a vent and a sealing gasket. The cathodes, anodes, and separators are inserted into the can. The final steps before testing are electrolyte filling (residues of electrolytes can occur here), sealing and activation of the cell.

After testing, cells that do not reach the desired quality and performance can be discarded of.

Waste streams from alkaline battery manufacturing can include:

- Residues of MnO_2 and graphite
- Failed batched of paste and cathode
- Residues of Zn powder and gelling agent
- Failed batches of paste and anode
- Residues of electrolyte
- Defective cells.

Figure 15. Simplified flow-chart of the manufacturing process of alkaline-based batteries and the related battery manufacturing waste



Source: based on (TDRFORCE, 2023)

2.1.2.5. Zinc-based battery manufacturing waste

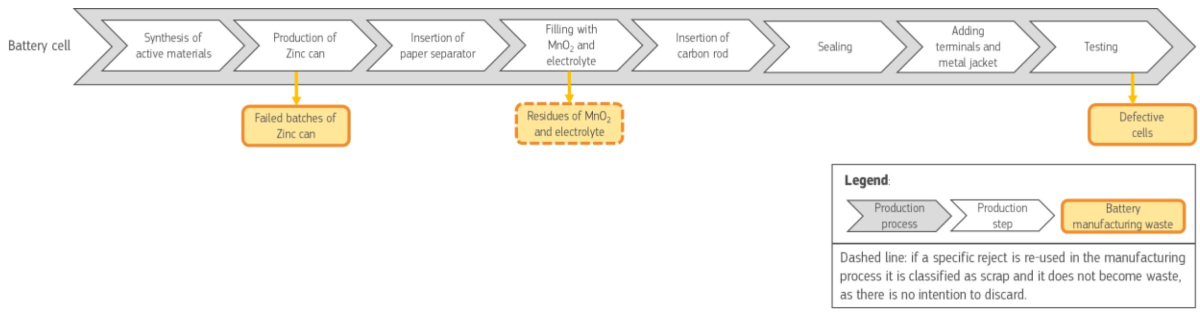
In the following, we illustrate only the production of the most representative Zn-based battery: the Zn-C battery.

The production of **Zn-C** batteries (see **Figure 16**) starts with synthesis of active materials and the production of the Zinc can, which is both the case and the anode. A separator made of paper is inserted in the Zinc can to prevent short-circuiting. The cathode material (manganese dioxide and electrolyte) is added in powder form and a carbon rod is placed in the centre of the battery. The battery is then placed in a resin tube and the plastic gasket, negative and positive terminals are added. Before testing, the metal jacket is added.

Manufacturing waste can be generated at any step of the manufacturing process. Typical residues can include:

- Failed batches of the Zinc can
- Residues of MnO_2
- Residues of electrolyte
- Defective cells.

Figure 16. Simplified flow-chart of the manufacturing process of Zn-C batteries and the related battery manufacturing waste



Source: based on (FDK, 2024; Sundén, 2019)

2.1.2.6. *Sodium-based battery manufacturing waste*

Sodium-based batteries are currently under development (no full scale production to date). Rejects from sodium-based battery manufacturing are expected to be analogous to the ones generated in the production of lithium-based batteries (see **Figure 12**).

2.1.3. Waste batteries

Lead-, Nickel-Cadmium (Ni-Cd) and Mercury- based batteries: the initial assessment is that these batteries should not be the object of a potential revision of List of Waste entries, as they are already adequately classified. The current classification for these entries is as hazardous waste (see Section 1.2.4) and there is no evidence to support a change in this classification. The only changes suggested consist in keeping the nomenclature harmonised and consistent with the changes proposed for other categories.

To cover the broad variety of **lithium-based batteries (Li-based batteries)**, the most common lithium battery types are under scope, namely **LCO, LMO, NMC, NCA, LTO, LFP, and LiSOCl**. Each of the seven selected types of lithium-based batteries has a different chemical composition. Typically, the composition of the cathode makes the difference between battery chemistries. The anodes of most lithium-based batteries are graphite-based. Liquid electrolytes are typically used for Li-based batteries but these are believed to be the root cause of many challenges of conventional Li-based batteries (e.g. electrochemical instability (thermal runaway), volatility and flammability, tendency to grow dendrites which cause short-circuits) (Huang, Shao, and Han 2022; H. Li 2023). In recent years, solid state batteries entered the market. Their working principle is similar to that of conventional lithium ion batteries, but SSB use a solid electrolyte instead a liquid electrolyte. Due to expected future development, SSB batteries are also under scope.

For nickel-based batteries (Ni-based batteries), **Nickel-Metal-Hydride (NiMH) and Na-NiCl$_2$ batteries** are under scope. The NiMH rechargeable battery replaced Ni–Cd batteries[21] for portable consumer use. NiMH-batteries are also used in hybrid vehicles. Na-NiCl$_2$ batteries have been introduced into the market for electric vehicles, mainly for public transport, but currently this type of battery is also used for stationary backup, railway backup, electric vehicles and on-grid/off-grid energy storage applications (EASE, 2016).

Alkaline-based batteries are non-rechargeable (primary) batteries and are already listed in the List of Waste under the waste code 16 06 04 as **absolute non-hazardous waste**. However, this type of battery could contain certain chemical compounds (e.g. certain Zn- and Mn-compounds but also electrolytes) with hazardous properties and is therefore further scrutinised in this project.

The current List of Waste contains a non-specific waste code for 'Other batteries and accumulators' (16 06 05, **absolute non-hazardous**). Frequently, used batteries that are associated to this unspecific waste code are **zinc-based batteries** as for example Zn-C, Zn-Cl and Zn air batteries. Zinc based batteries are often used in low-drain devices, such as battery-operated toys and remote controls. Similar to alkaline-based batteries, the zinc-based batteries could contain substances with hazardous properties and are therefore also assessed in the scope of this project.

As the common types of **silver containing batteries,** Ag-Zn and Ag-oxide, contain also a significant amount of zinc, these batteries are grouped with the mentioned Zn batteries in this project. Silver containing batteries often have the format of button cells and are commonly used in watches and other small devices (e.g. hearing aids).

For **sodium-based batteries,** NaS and Na-ion batteries with cathode material consisting of prussian white[22], layered oxide or polyanion are under scope. Na-S batteries are a type of molten-salt battery that uses liquid sodium and liquid sulphur electrodes and these batteries have a similar energy density to lithium-based batteries. Sodium ion batteries are similar in design and construction to Lithium ion

[21] The sale of consumer Ni–Cd batteries has been banned effective 2016 within the EU except for certain specific application (Batteries Directive, 2006/66/EC)

[22] Na-ion battery cathodes may use a "Prussian blue" analogue i.e. metal hexacyanide compound based on iron (ferrocyanide) or other metals (e.g. $Na_2Fe[(Fe(CN)_6]$ hexacyanoferrate based sodium rich iron)

batteries but rely on sodium compounds rather than on those of lithium. For a Na-ion battery, mainly soda ash (sodium carbonate) is used as a sodium precursor, this compound being far more abundant and sustainable to extract and refine than lithium. The cost of Na-ion batteries is expected to be significantly lower than that of lithium-based batteries (Abraham, 2020). This suggests that these batteries will also come into the market in large quantities in the coming years and are therefore also in scope of this study.

The following **Figure 17** offers a graphical overview on the battery chemistries and the specific battery types in scope.

Figure 17. Overview on the battery chemistries and the specific battery types under scope

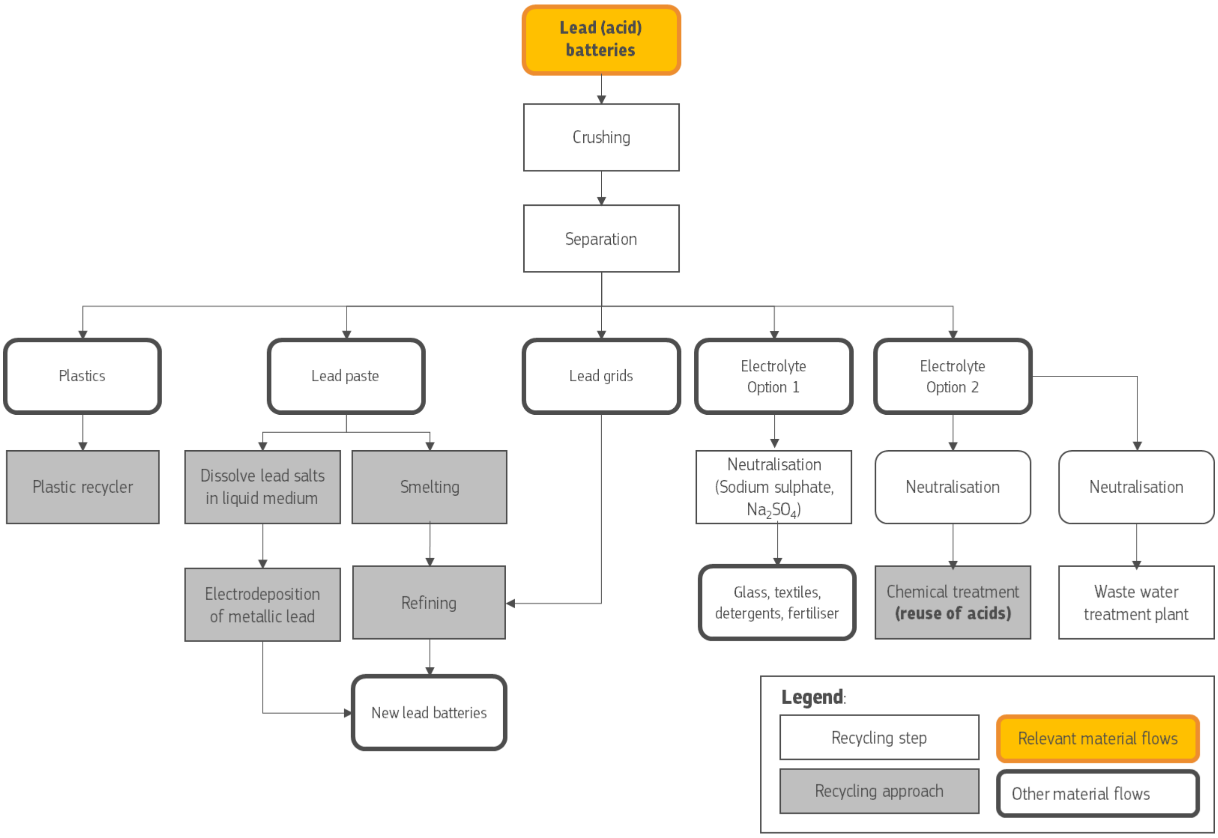
Battery type	Battery chemistry
Lead-based	PbA: Lead-acid battery
Lithium-based	LCO: Lithium-Cobalt-Oxide LMO: Lithium-Manganese-Oxide NMC: Lithium-Nickel-Manganese-Cobalt-Oxide NCA: Lithium-Nickel-Cobalt-Aluminium-Oxide LTO: Lithium-Titanium-Oxide LFP: Lithium-Iron-Phosphate $LiSOCl_2$: Lithium-Thionyl-Chloride
Nickel-based	NiMH: Nickel-Metal-Hydride $Na\text{-}NiCl_2$: Sodium-Nickel-Chloride
Alkaline-based	$Zn\text{-}MnO_2$: Zinc-Manganese dioxide
Zinc-based	Zn-C: Zinc-Carbon Zn-Cl: Zinc-Chloride Zn-air Ag-Zn: Silver-Zinc Ag-O: Silver-Oxide
Sodium-based	Na-S: Sodium-Sulphur Na-ion: Cathode made of Prussian white, layered oxide or polyanion

2.1.4. Intermediate material flows from waste batteries treatment

2.1.4.1. Lead-acid batteries

The first step of lead battery recycling is crushing for example with a hammer mill, followed by a separation of lead paste, lead grids, metallic plates and connectors, polypropylene and other plastics, and the acid electrolyte. These different fractions are then handled in subsequent recycling steps. The plastic parts can be used by plastic recyclers for example to produce new battery containers and other plastic products. Lead, in the form of lead metal and paste is refined in a lead smelting process to produce lead that can be used in new lead-based batteries. Another option is to dissolve lead in a liquid medium followed by an electrodeposition of the metallic lead. Lead grids are usually directly refined. The electrolyte, the sulphuric acid, can be converted to sodium sulphate which can be used for different purposes such as in glass, textiles, detergents, but can be used as well in fertilisers and laundry detergents. Certain approaches aim for the recycling of the electrolyte (acid) (**Figure 18**; (Ballantyne et al., 2018); Basel (2003)).

Figure 18. Simplified flow-chart of mechanical waste lead-acid battery recycling



2.1.4.2. Lithium-based batteries

Depending on the type of battery, discharging the lithium-based battery is the first treatment step, followed by a dismantling step in the case of battery packs. Dismantling allows the recovery of certain metals such as aluminium and steel from the casing, but also plastics, electronics and cables. Certain operators perform a thermal treatment step (pyrolysis), in some cases before dismantling.

To obtain black mass but also to recover other battery components, the battery or battery manufacturing waste undergoes mechanical stress in the form of crushing and shredding. Less common treatments are solvent treatment and calcination. Crushing can be carried out in an inert atmosphere (N_2, CO_2, CO and Ar), in brine, or using other systems to prevent fire risks (e.g. air/gas removal from crushing chamber).

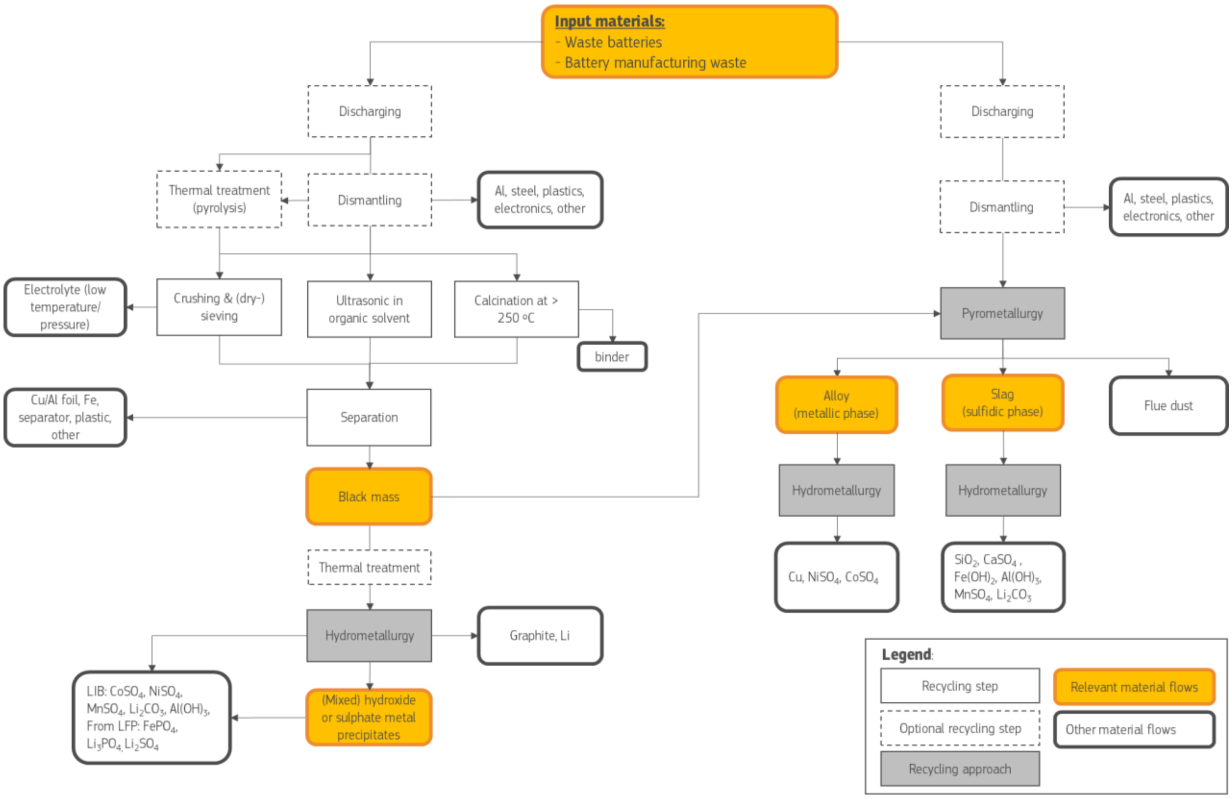
The separation of ferrous, non-ferrous metal fractions and foil as well as plastic is carried out through state of the art technologies (e.g. sieving, magnetic separation, eddy current separation, density separation in air and liquid). The recovery of graphite or electrolytes has not been implemented on a large scale yet. The recovered black mass is used as feedstock to hydrometallurgical or pyrometallurgical processes to recover valuable metals.

Several intermediates can be produced in a hydrometallurgical recycling process starting with black mass before a final product (e.g. a metal salt that can be used for battery material production) is reached. With acid treatment and following precipitation step(s), different (mixed) metal precipitates (so called Mixed Metal Precipitates or Mixed Hydroxide Precipitates (MPH)) but also other chemical species are produced. These precipitated salts are still an intermediate in the recycling process. Other intermediates could and will evolve in the coming years and are included in the scope.

In case of pyrometallurgical recycling the outputs are an alloy, slag and flue dust. The alloy and slag have to undergo further hydrometallurgical treatment to recover the valuable elements contained therein (alloy: Cu, Ni, Co; slag: Si, Ca, Fe, Al, Mn, Li).

Figure 19 gives an overview on the recycling steps and recycling approaches for lithium-based batteries and lithium battery manufacturing waste as well as the material flows from the different recycling steps or approaches. A distinction is made between material flows that are under scope (relevant material flows) and other material flows. In the case of other material flows, it is assumed that they are either not a waste flow (e.g. having been recycled into a product, or destined for recovery) or that they fit under already existing entries in the List of Waste, under different, non-battery specific categories. **Relevant material flows** are therefore both battery-specific and not currently suitably classified under existing waste codes. Detailed and recent surveys on the recycling of lithium-based batteries can be found in dedicated studies (ASYS, 2022; Latini et al., 2022; Wu et al., 2023; Yadav et al., 2020; Yu et al., 2021; Zhang et al., 2021).

Figure 19. Simplified flow-chart of mechanical (left) and pyrometallurgical (right) waste lithium-based battery recycling

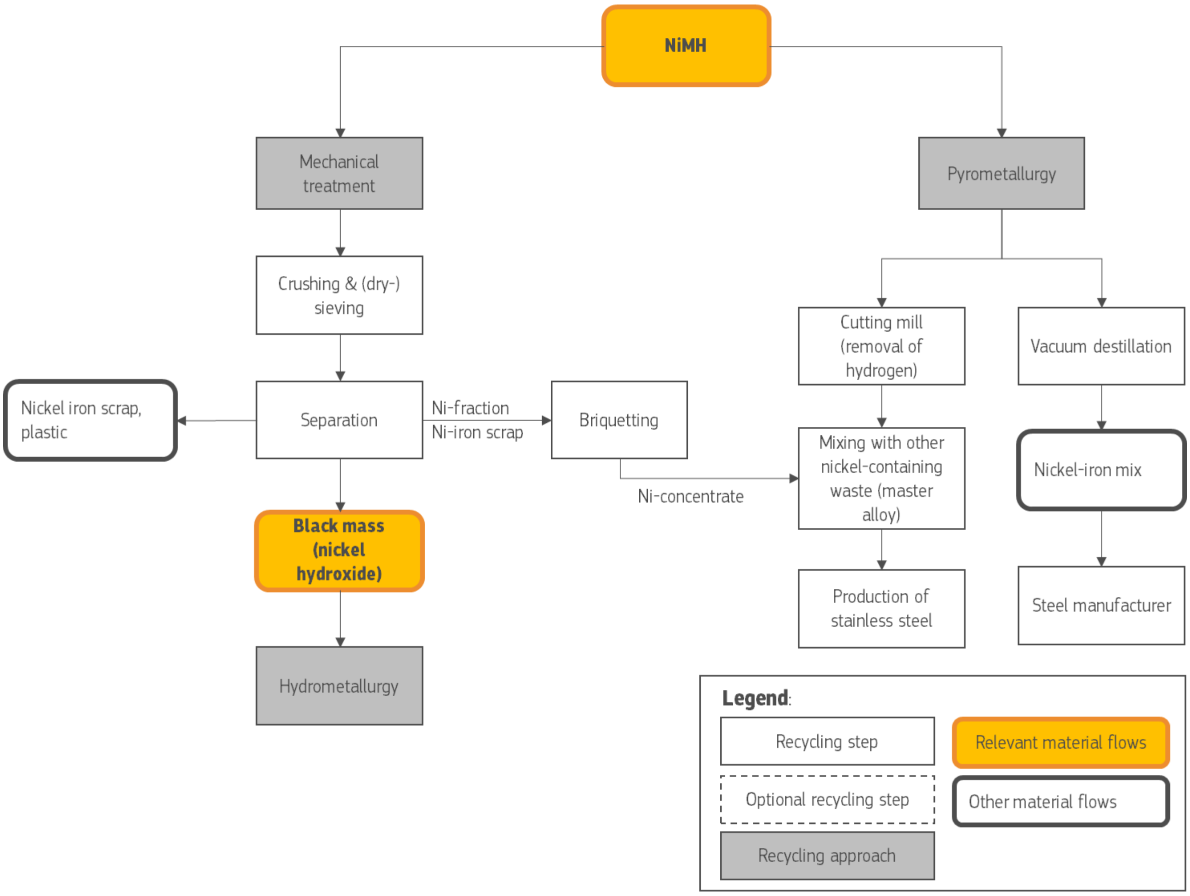


2.1.4.3. Nickel-based batteries

Nickel-Metal-Hydride batteries can be recycled with mechanical- and pyrometallurgical processes. With the mechanical approach, the NiMH waste batteries are crushed in the first place. Nickel-iron scrap and plastic are separated to recover an active black mass, mainly consisting of nickel-hydroxide.

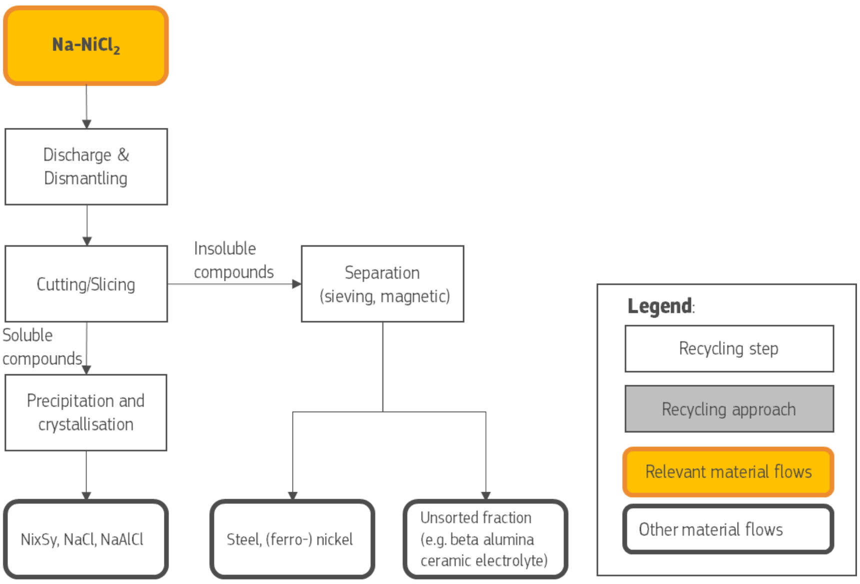
Vacuum distillation is a proven approach to recycle Ni-Cd batteries and can also be used for **NiMH batteries**. In a first step, a furnace is evacuated to 0.1 mbar with oven temperature of 100 to 150 °C. This is followed by further heating to 750 °C. In the furnace remains a nickel-iron mixture and an oil-water mixture. The nickel-iron mixture is separated and can be transferred to steel manufacturers (Accurec, 2023). In a second known recycling process, the batteries are first opened in a cutting mill. The batteries are then mixed with other nickel-containing waste and can be used as a master alloy for the production of stainless steel (**Figure 20**) (Holmberg, 2017).

Figure 20. Simplified flow-charts for nickel-metal-hydride waste battery recycling



Completely discharged and dismantled **Na-NiCl$_2$ batteries** are sliced and soluble components, such as NiCl$_2$, NaCl, and NaAlCl are leached out. These soluble components are further separated by precipitating the nickel as nickel sulphide, and by the subsequent crystallisation of NaCl and NaAlCl from the solution. The insoluble case material and ceramics undergo mechanical sieving and magnetic separation, and the valuable metals are recovered for metallurgical processing and subsequent reuse (**Figure 21**). The relatively valuable beta alumina ceramic electrolyte is currently not recycled (Armand et al., 2023).

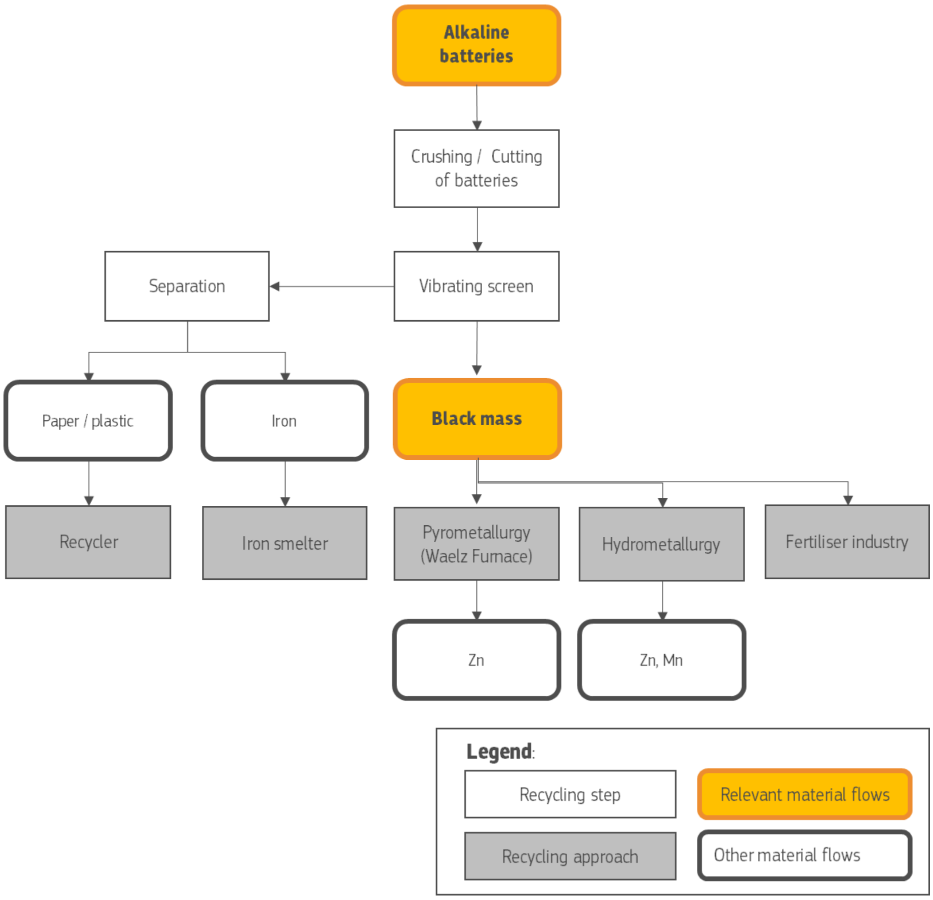
Figure 21. Simplified flow-charts for sodium-nickel-chloride waste battery recycling



2.1.4.4. Alkaline-based batteries

Alkaline-based batteries can be recycled together with carbon-based batteries in a smelting process (e.g. imperial-smelting-process, see Section 2.1.4.5). The aim is the recovery of the zinc. Another approach is the mechanical recycling of waste alkaline-based batteries (**Figure 22**). The first step is basically the separation of alkaline-based batteries from a mixed battery waste stream. This is done automatically (e.g. separation of button cells on a hopper) and/or manually. The alkaline battery fraction is then automatically sorted by size, shredded or cut and the active materials are removed from the internal casing by mechanical force (e.g. chain disrupter). On a vibrating screen the active materials and the casing are separated into two different fractions. With further separation techniques, the two fractions paper/plastic and iron can be recovered (Envirobat-España 2023). The resulting zinc- and manganese- rich black mass can be recycled in pyrometallurgy and hydrometallurgy recycling processes. Black mass recovered from alkaline-based batteries can also be used as constituent of fertilisers for plants, given the presence of the micronutrients zinc and manganese (Tracegrow, 2023).

Figure 22. Simplified flow-chart of alkaline waste battery recycling



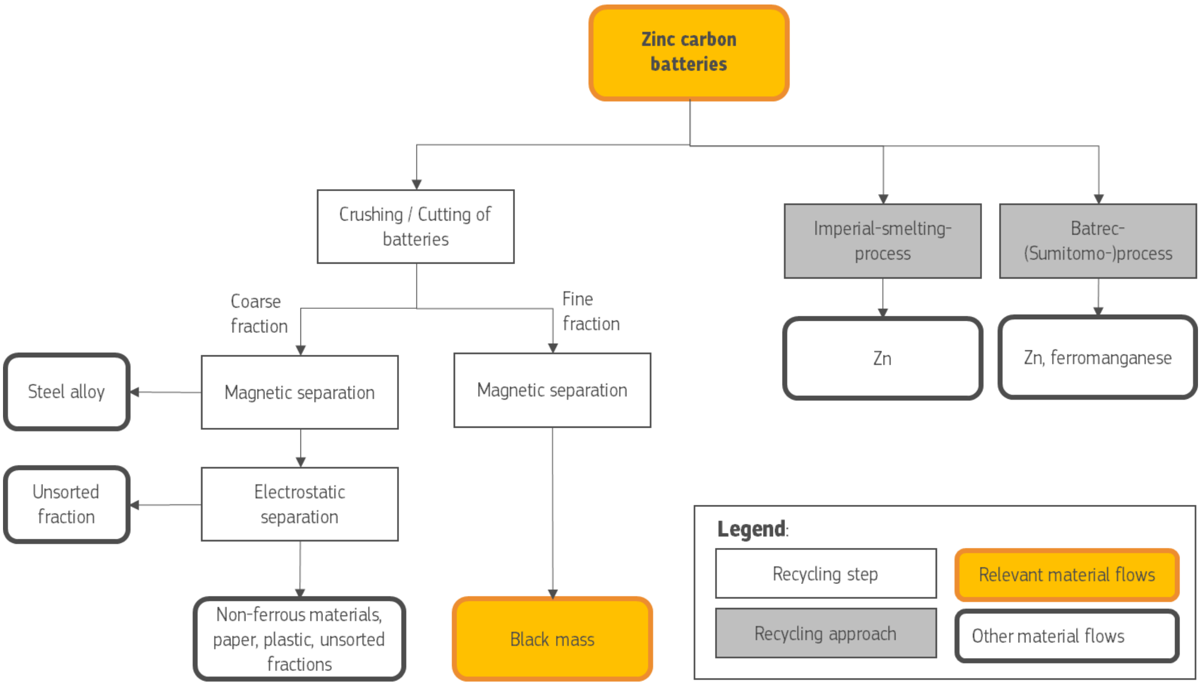
2.1.4.5. Zinc-based batteries

Zinc-based batteries can be recycled either mechanically or via pyrometallurgical processes (**Figure 23**). With mechanical recycling, the aim is to recover a zinc- and manganese- rich black mass. To obtain the black mass, the batteries undergo as a first step a mechanical stress in the form of crushing or cutting. From the black mass bearing fine fraction, magnetic metals are removed. The coarse fraction is further treated to recover steel alloy, non-ferrous materials, paper and plastic.

Zinc-carbon, zinc-air and alkaline-manganese batteries contain significant amounts of zinc, which is the main focus in the recycling of these waste batteries. In the recycling of zinc-containing batteries, the Imperial Smelting process is the most significant process. The zinc-containing batteries are fed into the smelting furnace together with coke. The zinc evaporates and leaves the furnace together with the waste gases. In an absorber, liquid lead is blown into the exhaust gases as a fine mist. Zinc forms an alloy with the lead droplets and can be pumped off. Cooling causes the mixture to separate into lead and zinc again. Zinc can be tapped off in liquid form and further processed (OCDE, 1995).

In the Batrec (Sumitomo) process (Batrec, 2023), spent batteries are heated to 600–750 °C in a shaft furnace. The gases produced during the pyrolysis process are then completely oxidised in an afterburner chamber. The battery residues from the pyrolysis are fed into a melting furnace and heated up to 1,500 °C. In a reducing atmosphere, the oxides contained are reduced with the addition of carbon and magnesium oxide and the metals are melted. Zinc evaporates and is fed into an absorber and the liquid zinc condenses. The smelting furnace still contains slag and ferromanganese, which are easy to separate due to their different densities. The ferromanganese is supplied to steelworks as a master alloy.

Figure 23. Simplified flow-chart of mechanical (left) and pyrometallurgical (right) zinc-based waste battery recycling



2.1.4.6. Sodium-based batteries

Sodium-based batteries are a promising electrical power source, but compared to the other batteries under scope, are still not very widespread on the market. It is therefore still unclear how sodium-based batteries will be recycled in the future. (Zhao et al., 2023) highlight, that SIB and lithium-based batteries have similar structures and material components. Therefore, waste SIB could be recycled using established recycling technologies for lithium-based batteries (see **Figure 19**), although some modifications are needed. After discharge and dismantling, SIB may be shredded to gain a fine grained powder (similar to black mass). Compared to lithium-based batteries, further treatment of the pulverised SIB is more straightforward than lithium-based batteries because SIB contain an abundance of sodium and simplified material.

2.2. Methodology

The methodology adopted to direct the course of the project follows the consecutive steps which are described in more detail below: review of current LoW and adaptation in MS; hazard determination; classification of waste streams in scope; and recommendation for a potential LoW amendment. These steps are then summarised in Section 2.2.5 below.

2.2.1. Review on classification in Member States

Novel battery chemistries (since the latest revision of the LoW) which are already being produced and put on the market, can end up in different waste streams (e.g. separately collected, part of another waste, e.g. batteries in WEEE or ELV) and may already be recycled in some cases. Waste streams related to batteries that currently do not have a specific waste code need to be assigned to existing waste codes from the EU LoW or – in case the EU LoW was adapted by Members States – the adapted waste codes can be used. The challenge is that the current waste codes from the EU LoW may not reflect the (hazardous) characteristics of the battery waste stream being considered.

In order to gain a better understanding of how the battery related waste stream under scope are currently classified in Member States, a first consultation (consisting of a survey) involved the Expert Group of Waste[23]. Furthermore, bilateral meetings with battery recyclers have been organised to complement the WEG knowledge.

2.2.2. Review of EU LoW adaptation in Member States

As part of the consultation of the Expert Group on Waste, the question of the extent to which the List of Waste has already been adapted or will be adapted to new battery chemistries in the near future in the Member States was clarified. In case the LoW is already adapted, the relevant background information for the classification of the waste streams is given (see **Table 4**).

2.2.3. Hazard determination

The Commission provides technical guidelines on the classification of waste[24]. These guidelines are the basis for the determination of hazardousness. The five steps to classify a waste are described in the paragraphs below and are summarised in a flow chart in **Figure 25**.

2.2.3.1. Step 1 – Waste composition

The assessment is based on the concentration of materials in the waste stream. For metals, chemical analysis does not always identify the specific substance (chemical compound) but rather the elemental composition of the waste. However, this is not enough, as the knowledge of the precise chemical compound of a metal is often crucial (e.g. for manganese (Mn) whether it is e.g. MnO or MnO_2). In order to determine whether it is appropriate to propose mirror entries for any given waste, knowledge about the variability of the composition should also be available (e.g. 20–30 % MnO_2).

For the specific case of batteries being reviewed in this report, it is important to consider that due to the nature of the electrochemical reactions that occur in the battery, its composition varies according to its state-of-charge, i.e., the relative concentrations of the reactive species vary since the reactions between the different species are involved in the production of current during use. Therefore, the precise determination of relative concentrations is not relevant, but determining a range of concentrations representing the operating charge-discharge reactions and beyond (in case of damage, overcharge, short-circuit or others) should be considered. For instance, charged waste alkaline-based batteries will contain MnO_2 (with assigned hazard property HP6) and traces of ZnO, but conversely, discharged batteries will contain ZnO (HP14) and traces of MnO_2. In any case (and also because the state of charge is not usually[25] measured or established at the waste stage), hazardous classification will be triggered (COMEPA, 2018).

To build knowledge on battery composition, a comprehensive database for all waste streams defined in the scope of this study was assembled. The following sources were used for this purpose: scientific literature, industry position papers, consultation of the Waste Expert Group, bilateral meetings with battery manufacturers, recyclers and battery associations, safety data sheets from battery

[23] The Expert Group on Waste assists the Commission for example in relation to the implementation of existing Union legislation, programmes and policies, the preparation of delegated acts, and the preparation of legislative proposals and policy initiatives (https://ec.europa.eu/transparency/expert-groups-register/screen/expert-groups/consult?lang=en&do=groupDetail.groupDetail&groupID=03343)

[24] TGCW - Commission notice on technical guidance on the classification of waste (2018/C 124/01) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018XC0409(01)

[25] This should however change for LMT, Industrial and EV batteries, with the use of the battery passport. Cf. BWBR Annex XIII § 4 (d).

manufacturers, retailers and recycling plant operators, plant visits, conference participation, and a stakeholder consultation.

2.2.3.2. Step 2 – Assigning Hazard Statements Codes and associated Hazardous Properties

Hazard Statement Codes (e.g. H300) are linked to a **hazard class** (H300 = Acute Tox.1 (oral)) set by the CLP regulation (and adapting the GHS); for waste, this can in turn relate to **Hazardous Properties** (e.g. HP 6 – acute toxicity, as per Annex III of the WFD; listed in **Annex 1** of the present document). Once hazard statements have been identified in Step 2, this allows identification of the hazardous properties they are linked to, for consideration in all subsequent steps. The C&L Inventory, provided by ECHA ((ECHA, 2023) https://echa.europa.eu/information-on-chemicals/cl-inventory-database)) is used in this work to link the substances found in the battery related waste streams with the Hazard Statement code and its related Hazardous Properties. The CL inventory database contains classification and labelling information on notified and registered substances received from manufacturers and importers. It also includes the list of harmonised classifications. Examples for the hazard classification of manganese and different chemical compounds thereof are given in **Figure 25**. This figure highlights, that a detailed knowledge on the precise chemical compound is crucial to assess the hazardousness of a waste. Exemplarily, manganese and manganese oxide are not classified; in comparison, manganese dioxide (MnO_2) and manganese within the cathode mixtures that are used in NMC lithium-based batteries are assigned certain hazard classes and hazard codes.

Figure 24. Excerpt from the CL inventory for manganese as an element and for manganese in various chemical compounds (MnO, MnO_2, and manganese within a lithium-nickel-manganese-cobalt-oxide mixture used as cathode material for NMC)

Name	EC / List no.	CAS no.	Classification	Source
Manganese	231-105-1	7439-96-5	Not Classified	REACH registration C&L
Manganese oxide	215-695-8	1344-43-0	Not Classified	REACH registration C&L
manganese dioxide 025-001-00-3	215-202-6	1313-13-9	Acute Tox. 4 Acute Tox. 4	Harmonised C&L
Lithium Nickel Manganese Cobalt Oxide (LiNi0.8Mn0.1Co0.1O2)	878-728-0	179802-95-0	Skin Sens. 1 Resp. Sens. 1 Carc. 1A STOT RE 1	Notified C&L

2.2.3.3. Step 3 – Hazardous Properties (HP1–HP15)

This step consists of the assessment of hazardous properties according to the WFD Annex III (cf. **Annex 1** the present document).

- **Step 3.1 Assessment of Hazardous Properties with limit values**

Concentration limit values have been assigned for the hazardous properties HP4–HP8, HP10, HP11, HP13, and HP14. A waste needs to be **classified as hazardous if the concentration limits for the substances concerned are equalled or exceeded**.

In the following report, if a concentration limit is exceeded, the hazard classification is highlighted with a Y (Yes), in case the concentration limit is below the limit value with an N (No). In some cases, especially if a chemical compound in a waste stream can have a high variability, a classification is not always certain. For example, the proportion of lithium-manganese-oxide (LMO) in lithium-based batteries is 20–50 % (see **Table 9**). LMO is assigned the hazard statement codes H302, H332 and H413 with a concentration limit, respectively, of ≥ 25 %, ≥ 22.5 % and ≥ 25 %. In this case it is highly probable, that the limit values will be exceeded. The hazard classification is then flagged via a degree symbol (°), and due to the high probability of exceedance also marked with a Y (°Y = highly probable that the concentration limit will be exceeded and a hazard classification is triggered).

- **Step 3.2 Assessment of Hazardous Properties without limit values**

No concentration limits have been assigned for hazardous properties, HP1–HP3, HP9, HP12 and HP15. If a waste is identified as having significant amounts of a substance with **any of these hazardous properties**, the waste is generally **automatically classified as hazardous**, unless appropriate testing is done and demonstrates that the waste is non-hazardous. For HP12 and HP15, the referred Commission Notice on waste classification provides further quantitative and qualitative guidance, associated to the presence of substances to which certain hazard statements are assigned.

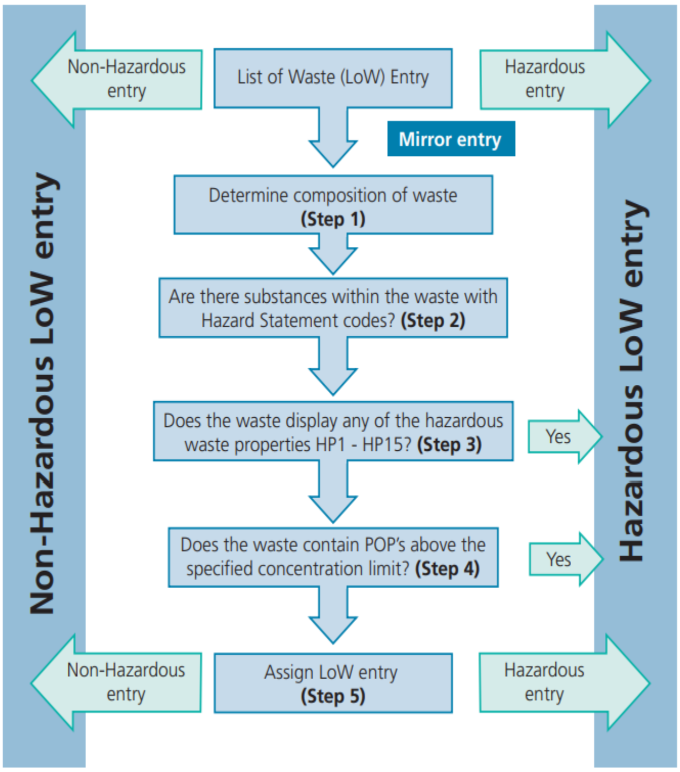
2.2.3.4. Step 4 – POPs in waste

As described in the Annex of Decision 2000/532/EC, wastes containing certain persistent organic pollutants (POPs[26]) exceeding the concentration limits indicated in Annex IV of the POP regulation[27], are directly classified as hazardous (see Annex 2**, Table 40**). If a waste contains other POPs as for example endosulfan, hexachlorobutadiene, polychlorinated naphthalenes, SCCPs, PFOS, the POP-BDEs, and HCBD, the waste shall be assessed against the POPs Regulation and the reference concentration limits for the relevant hazardous properties in accordance with the procedures described in **Step 3**.

2.2.3.5. Step 5 – List of Waste Entry

After completion of Steps 1 to 4, and based on the conclusions derived on the hazardousness of the waste, an **appropriate hazardous or non-hazardous entry** from the List of Wastes is assigned.

Figure 25. Flow chart for determining whether hazardous or non-hazardous entry is to be assigned (EPA, 2019)



[26] polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF), DDT (1,1,1-trichloro-2,2- bis (4-chlorophenyl) ethane), chlordane, hexachlorocyclohexanes (including lindane), dieldrin, endrin, heptachlor, hexachlorobenzene, chlordecone, aldrine, pentachlorobenzene, mirex, toxaphene hexabromobiphenyl and/or PCB

[27] Regulation on persistent organic pollutants, Regulation (EC) No 850/2004 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004R0850

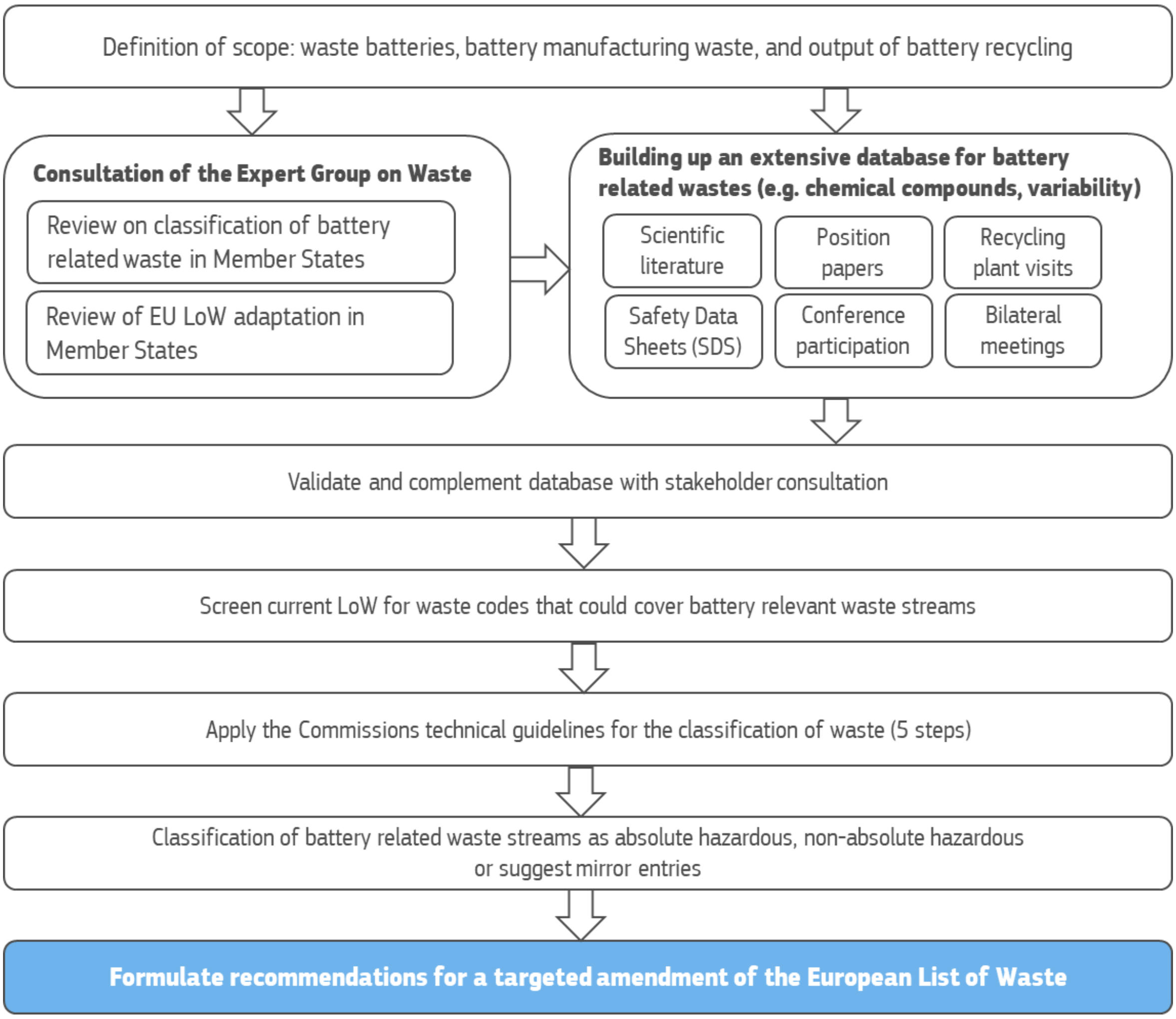
2.2.4. Recommendation for a potential amendment of the EU LoW

To prepare a potential amendment of the EU LoW, the current EU LoW and national Lists of Waste are analysed (see section 3.4). After the identification of the different battery waste relevant streams and their classification, the missing LoW entries for these waste are identified. Based on the classification of the battery waste, the JRC is proposing technical recommendations for a potential amendment of the EU LoW as the outcome of this project.

2.2.5. Overview of the project methodology

The following **Figure 26** provides a summarised overview of the applied methodology.

Figure 26. Overview on the methodology to classify battery related wastes and to support a proposal to amend the EU List of Waste



3. Waste codes currently applied to battery related waste

3.1. Waste codes for battery manufacturing waste

NB: As a general remark, the exploration of the waste codes below relates to waste which is specifically related to batteries. As detailed in the technical guidance on waste classification, waste will be listed according to its characteristics and origins; waste that is generated in the course of the activity of battery manufacturing but not related to batteries (e.g. packaging, paper and cardboard from office activity, etc.) should be classified according to generic relevant categories.

3.1.1. Lead-acid batteries

Lead manufacturing facilities are usually large and established plants, often vertically integrated with primary or secondary lead processing. Various wastes arising from the processes might be currently assigned to chapter 10 04 "wastes from lead thermal metallurgy".

Lead battery manufacturing itself may give rise to rejected lead plates, lead pastes (oxides or sulphates) and acids, often reused internally into the process, or constituting wastes classified under several non-specific, hazardous or non-hazardous codes (e.g. 10 04, 06 01 MFSU of acids, 12 01, 19 10 and even 16 06 01 if a battery has been formed).

3.1.2. Lithium-based batteries

Stakeholder consultation has enabled the JRC to obtain data sets of manufacturing waste originating from most lithium battery chemistries from five different organisations. Most data received corresponds to NMC batteries, with no data on LiSOCl. The consultation revealed that absolute non-hazardous and absolute hazardous waste codes are being applied to the manufacturing waste from lithium-based batteries (**Table 2**).

In principle, non-hazardous waste codes are used for waste from anode production (e.g. anode electrode cut-offs waste, anode powder, anode slurry, anode foils, coated anode foils). This is because the anode and its current collector consists in most cases of non-hazardous substances (e.g. graphite, copper foil).

In contrast to the above, waste from cathode production (e.g. cathode electrode cut-offs waste, cathode powder, cathode slurry, coated cathode foils) is allocated to a hazardous waste code. As soon as the anode and cathode is combined to a battery cell, the dry- and wet cells, packs and modules that are off specification are in most cases assigned an absolute hazardous waste code. However, in some cases also absolute non-hazardous codes are being used by operators.

With the exception of the sub-chapters 16 06 and 20 01, the waste codes currently used belong to chapters that are not connected to batteries, but to other waste chapters related to wastes generated by other industries or addressing broad process categories:

- 06 wastes from inorganic chemical processes
  - 06 01 wastes from the manufacture, formulation, supply and use (MFSU) of acids
  - 06 03 wastes from the MFSU[28] of salts and their solutions and metallic oxide
- 11 wastes from chemical surface treatment and coating of metals and other materials; non-ferrous hydro-metallurgy
  - 11 01 wastes from chemical surface treatment and coating of metals and other materials
- 12 wastes from shaping and physical and mechanical surface treatment of metals and plastic
  - 12 01 wastes from shaping and physical and mechanical surface treatment of metals and plastics
- 16 wastes not otherwise specified in the list
  - 16 01 end-of-life vehicles from different means of transport
  - 16 03 off-specification batches and unused product
  - 16 06 batteries and accumulators

[28] Wastes from the Manufacture, Formulation, Supply and Use (MFSU)

- 17 construction and demolition waste
    - 17 04 metals (including their alloys)
- 19 wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use
    - 19 10 wastes from shredding of metal-containing wastes
    - 19 12 wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified
- 20 municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions
    - 20 01 separately collected fractions (except 15 01)

Table 2. Waste codes assigned to waste streams from lithium-based battery manufacturing

Lithium battery manufacturing waste streams	**Sample 1 (LCO, LMO, NMC, NCA, LTO, LFP)**	**Sample 2.1 (LFP)**	**Sample 2.2 (NMC)**	**Sample 3 (NMC)**	**Sample 4 NMC**	**Sample 5 (NMC)**
Anode electrode cut-offs waste	N/A	N/A	N/A	16 03 04	N/A	N/A
Cathode electrode cut-offs waste	N/A	N/A	N/A	16 03 03*	N/A	N/A
Anode powder	16 03 04	N/A	16 03 04; 12 01 02	N/A	No data, but considered as ANH	N/A
Cathode powder	06 03 15*, 16 03 03*, 19 12 11*	N/A	16 03 03*, 19 12 11*, 06 03 15	N/A	06 03 15*, 16 06 03*	N/A
Anode slurry	N/A	N/A	11 01 10	Not clear/unclear	No data, but considered as ANH	N/A
Cathode slurry	N/A	N/A	11 01 09*; 06 05 02	14 06 03*	06 03 13*, 11 01 11*, 16 03 03*	N/A
Anode foils	12 01 03, 12 01 04, 12 01 99, 16 03 04, 17 04 01, 19 10 02, 19 12 12	N/A	16 01 18, 16 01 21*, 19 12 03	N/A	No data, but considered as ANH	N/A
Cathode foils	12 01 03, 12 01 04, 12 01 99, 17 04 02, 19 10 02, 19 12 12	N/A	16 03 03*, 16 01 21*, 06 03 15, 19 12 03	N/A	No data, but considered as ANH	N/A
Coated anode foils	12 01 99, 16 03 04, 19 10 02	N/A	N/A	N/A	No data, but considered as ANH	N/A
Coated cathode foils	06 03 15*, 12 01 99, 16 03 03*, 19 10 02	N/A	N/A	N/A	No data, but considered as AH	N/A
Dry cells / Cells without electrolyte	16 03 03*, 19 10 02	16 03 03*	16 03 03*; 16 01 21*; 06 03 15	16 03 03*	N/A	16 03 03*
Wet cells / Cells with electrolyte	16 01 21*, 16 02 15*, 16 02 16, 16 06 06*	16 03 03*	16 03 03*; 16 01 21*; 16 06 05	N/A	N/A	16 03 05*
Jelly rolls	16 01 21*, 16 02 15*, 16 03 03*, 12 01 99, 19 01 17*	N/A	16 03 03*; 16 01 21*; 06 03 15; 19 12 03	N/A	N/A	N/A
Battery cell waste	N/A	N/A	N/A	16 06 06*	N/A	N/A
Shredded LFP cell material	N/A	19 12 11*	N/A	N/A	N/A	N/A
Modules - off spec	16 01 21*, 16 06 05, 20 01 35*, 20 01 36	16 03 03*	16 03 03*; 16 01 21*; 16 06 05	N/A	N/A	N/A
Packs - off spec	16 01 21*, 16 06 05, 20 01 35*, 20 01 36	16 03 03*	16 03 03*; 16 01 21*; 16 06 05	N/A	N/A	N/A
Electrolyte	N/A	N/A	16 06 06*	N/A	N/A	N/A

3.1.3. Nickel-based batteries

For nickel-based batteries, data is only available for Na-$NiCl_2$ batteries (FZSONICK, 2023). A detailed overview on the relevant waste streams, the materials included and the assigned waste codes is provided in Annex 3 (**Table 41**). The stakeholder providing the data below commented that the current EU LoW covers the manufacturing waste from the Na-$NiCl_2$ manufacturing well and no further entries are needed. Only for the waste stream from the production of the liquid cathode and the solid cathode hazardous waste codes are applied. For the Na-$NiCl_2$ manufacturing waste, waste codes are used from similar sub-chapters as for the lithium-based batteries:

- 01 wastes resulting from exploration, mining, quarrying, and physical and chemical treatment of minerals
  - 01 04 wastes from physical and chemical processing of non-metalliferous minerals
- 06 wastes from inorganic chemical processes
  - 06 03 wastes from the MFSU of salts and their solutions and metallic oxide
- 16 wastes not otherwise specified in the list
  - 16 01 end-of-life vehicles from different means of transport
  - 16 03 off-specification batches and unused product
  - 16 06 batteries and accumulators
  - 16 11 waste linings and refractories
- 19 wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use
  - 19 08 wastes from waste water treatment plants not otherwise specified

3.1.4. Alkaline-based batteries

Research carried out in the context of this study and associated stakeholder consultation has provided no specific information on manufacturing waste related to this type of batteries.

3.1.5. Zinc-based batteries

Research carried out in the context of this study and associated stakeholder consultation has provided no specific information on manufacturing waste related to this type of batteries.

3.1.6. Sodium-based batteries

Research carried out in the context of this study and associated stakeholder consultation has provided no specific information on manufacturing waste related to this type of batteries.

3.2.Waste codes for waste batteries

The consultation of the Member States on the current classification of lithium- and nickel-based batteries waste revealed an inhomogeneous picture in the EU (**Table 3**). In principle, six different waste codes are assigned to lithium-based and nickel-based batteries, in case the LoW is not already extended for this type of batteries.

In many cases, collected Li-based and Ni-based batteries are assigned to the non-hazardous waste code (16 06 05, other batteries and accumulators). However, some Member States already deviate from the classification in **Table 1** and assign Li-based but also Ni-based batteries to a hazardous waste code. Certain Member States even distinguish between the sources of the Li-based batteries.

Batteries are also part of waste electrical and electronic equipment (WEEE) and lithium-based batteries are an essential component of vehicles and remain therein upon these becoming end-of-life vehicles (ELVs). In case the batteries are separated from the WEEE or ELV, the batteries are associated to the non-specific waste code **16 02 15*** (hazardous components removed from discarded equipment; for WEEE) or to waste code **16 01 21*** (hazardous components other than those mentioned in 16 01 07 to 16 01 11 and 16 01 13 and 16 01 14; for ELV). However, after an extraction, the batteries fall under the Battery Regulation and should be assigned to a battery waste code (**sub-chapter 16 06**)."

In the case of Belgium, lithium- and nickel-containing batteries are even classified differently by the competent authorities of the three different regions. In the Brussel Region, the competent authorities consider Li-containing batteries as hazardous, while the Walloon and Flemish regions consider lithium-based batteries as non-hazardous for the time being.

Table 3. Waste lithium-based and waste nickel-based battery classification in selected EU Member States (consultation of the Expert Group on Waste)

Member State	Type of waste battery	16 01 21*[29]	16 02 15*[30]	16 06 02*[31]	16 06 05[32]	20 01 33*[33]	20 01 34[34]
AT	Li-based batteries from WEEE		x				
	Li-based batteries from ELV	x					
	Mix of Li-based batteries and NiMH batteries					x	
	NiMH and $NiCl_2$			x			
BE (Br)	Li-based batteries from WEEE		x				
	Li-based batteries from ELV	x					
	Li-based batteries unknown					x	
	Ni-based batteries			x			
BE (Fl)	Li-based batteries				x		
	Ni-based batteries				x		
BE (Wa)	Li-based batteries general				x[35]		
	Ni-based batteries				x[36]		
CZ	Li-based batteries (general)	x	x		x		
DE	Li-based batteries from WEEE		x				
					x[37]		
	Li-based batteries from ELV	x					
					x		
	NiMH				x		
DK	Li- and Ni-based batteries				x		
FI	Li-based batteries				x		
IR	Li-based batteries (general)	x	x		x	x	x
IT	Li-based batteries from municipal waste collection				x	x	
	NiMH				x		x
LT	Li- and Ni-based batteries		x				
LU	Li-based batteries of light means of transport and ELV				x		
	Mix batteries from WEEE: Li, Ni metal hydride, Ni-Cd					x	
NL	Li-based batteries					x	
SK	Li-based batteries	x			x		
	Nickel-based batteries			x	x		

[29] 16 01 21* hazardous components other than those mentioned in 16 01 07 to 16 01 11 and 16 01 13 and 16 01 14
[30] 16 02 15* hazardous components removed from discarded equipment
[31] 16 06 02* Ni-Cd batteries
[32] 16 06 05 other batteries and accumulators)
[33] 20 01 33* batteries and accumulators included in 16 06 01, 16 06 02 or 16 06 03 and unsorted batteries and accumulators containing these batteries
[34] 20 01 34 batteries and accumulators other than those mentioned in 20 01 33
[35] Adapted LoW to 16 06 05*
[36] Adapted LoW to 16 06 05*
[37] Germany submitted to the European Commission a notification under Article 7 of the WFD on 21st February 2024 informing of an individual classification of Li-ion batteries from electrical and electronic devices with code 16 06 05* (i.e. as hazardous waste for a normally absolute non-hazardous code).

3.3. Waste codes for intermediate material flows from battery waste treatment

3.3.1. Black mass from mechanical recycling

Currently the LoW does not include a specific waste code for black masses from mechanical treatment of any type of battery. The consultation of the Expert Group on Waste and the Stakeholder Consultation revealed that black mass received from Li- or Ni-based batteries are in most cases associated to the waste code **19 12 11*** (other wastes (including mixtures of materials) from mechanical treatment of waste containing dangerous substances). Depending on the composition, also other waste codes are applied in Member States, such as **19 10 05*** (other fractions containing dangerous substances) or **06 03 15*** (metallic oxides containing heavy metals). All waste codes applied for black mass are classified as hazardous.

Black mass from alkaline-based batteries is associated to two non-hazardous waste codes from sub-chapter **19 12** "wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletizing)", namely **19 12 03** (non-ferrous metal) and **19 12 12** (other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in **19 12 11**).

3.3.2. Alloy and slag from pyrometallurgical waste battery treatment

The consultation of the Waste Expert Group revealed that slags from pyrometallurgical battery treatment are associated to the following codes:

- 10 04 01* (slags from primary and secondary production)
- 10 04 02* (dross and skimmings from primary and secondary production)
- 19 01 11* (bottom ash and slag containing hazardous substances)

As with the black mass, the outputs of the pyrometallurgical battery treatment are associated to hazardous waste codes.

The stakeholder consultation showed, that in Belgium slags from pyrometallurgical lithium-based waste battery recycling are assigned to the **non-hazardous waste code 10 08 09 (other slags)**. However, stakeholders commented, that a new hazardous waste code (as a mirror entry) could be implemented to cover slags with hazardous properties.

3.4. National adaptation of the List of Waste

Article 7 of the Waste Framework Directive specifies that the list of waste "shall be binding as regards determination of the waste which is to be considered as hazardous waste". While some Member States have implemented in their national legislation additional waste codes that depart or complement those in the European List of Waste, as summarised in the next section for battery-relevant waste, the waste list has the clear purpose of harmonising the way waste is identified and classified in the EU. Consequently, Member States are expected and encouraged to follow this list and to notify the Commission about specific deviations in classification, as required under Article 7(2) and 7(3) of the Directive.

3.4.1. National adaption for waste batteries

The consultation of the Expert Group on Waste in early 2023 and further research revealed that several Members States classified lithium- and nickel containing batteries as hazardous waste and certain Member States already adapted or will adapt the LoW for lithium- and/or nickel-based batteries with specific national waste codes (**Table 4**). In case the LoW is already amended, the lithium- or nickel-based batteries entries are both non-hazardous and hazardous. However, the vast majority of the Member States do not have specific waste codes for those batteries.

The following sections offer an insight into the classification of lithium- and nickel-based batteries and the national adaptations of the EU LoW.

Austria added a hazardous waste codes for lithium-based batteries (EDM, 2022). Lithium-based batteries now have their own LoW entry (35337*). The entry for Nickel-Cadmium accumulators (LoW code: 16 06 02*) shall be used also for NiMH batteries and Na-$NiCl_2$ batteries (ZEBRA batteries). However, new hazardous national codes for NiMH and other nickel-based batteries are foreseen in an amendment of the Austrian Waste List Ordinance. Austria considers **all waste batteries as hazardous**.

In the Czech Republic, the intention is to add a non-hazardous waste code for batteries and accumulators containing lithium (16 06 05 01; consultation of the Expert Group on Waste).

Estonia adopted an extended national List of Waste for several types of batteries (NiMH, lithium ion batteries (rechargeable and non-rechargeable), silver oxide) by subdividing waste code 16 05 05 (03-06). These new battery types are classified as non-hazardous (Kliimaministeerium Estonia, 2007).

Germany: In February 2024, Germany notified the European Commission about an individual classification of Li-ion batteries from WEEE as hazardous under code 16 06 05* “other batteries and accumulators“, which is otherwise an absolute non-hazardous code.

France: The 2014 Ineris report (INERIS, 2014) confirmed hazardousness for lithium-ion batteries. Therefore, the French Ministry (Ministère de la transition écologique et de la cohésion des territoires) has drawn up an internal memo for the inspection departments indicating that the waste code to be applied for lithium-ion batteries by professionals is 16 06 05* "other batteries and accumulators". In France there is no regulatory act because the use of waste codes is the responsibility of the operator (French Environment Ministry, personal communication, 2024) .

Spain added two hazardous waste codes, one for lithium-based batteries and one for nickel-based batteries (Ni-Cd are excluded and are assigned to the existing 16 06 02* (BOE, 2021). An additional waste code was added for batteries containing other hazardous substances (16 06 09*). The waste codes in sub-chapter 20 01 were adapted accordingly (20 01 42-44*).

Table 4. Overview batteries classification in EU Member States (in alphabetical order)

Austria[38]	
35337*	Lithium batteries
35323*	Nickel-Cadmium accumulators: this code shall be used also for Nickel-Metal-Hydride accumulators and Sodium-Nickel chloride batteries (Zebra batteries)
35325*	New hazardous national code for "Nickel-metal-hydride accumulators and other nickel-based accumulators (except 35323*)" is foreseen in an amendment of the Austrian Waste List Ordinance
35335*	Zinc-Carbon batteries
35336*	Alkaline manganese batteries
Czech Republic (from 2025)	
16 06 05 01	Batteries and accumulators containing lithium
Estonia	
16 06 05 03	Nickel-metal hydride batteries
16 06 05 04	Lithium-ion batteries
16 06 05 05	Silver-oxide batteries
16 06 05 06	Lithium batteries, non-rechargeable portable batteries
Germany	
16 06 05*	Other batteries and accumulators

[38] Austria has not adopted the European List of Waste. The Austrian catalogue is less extensive, has a different (5-digit) numbering system and is not harmonized with the EU catalogue.

France	
16 06 05*	Other batteries and accumulators
Spain	
16 06 07*	Accumulators, cells or batteries in whose composition lithium is present in any form, such as lithium cells or lithium-ion accumulators
16 06 08*	Accumulators, cells or batteries containing nickel in any form, such as nickel metal hydride (NiMH) accumulators. Nickel-cadmium accumulators and batteries are excluded from this code
16 06 09*	Accumulators, cells or batteries containing other hazardous substances
20 01 42*	Accumulators, cells or batteries in whose composition lithium is present in any form, such as lithium cells or lithium-ion accumulators
20 01 43*	Accumulators, cells or batteries containing nickel in any form, such as nickel metal hydride (NiMH) accumulators. Nickel-cadmium accumulators and batteries are excluded from this code
20 01 44*	Accumulators, cells or batteries containing other hazardous substances

3.4.2. National adaption for intermediate fractions from waste battery recycling

The only Member State that implemented waste codes for intermediate fractions of waste batteries recycling processes is Lithuania with the implementation of two new waste codes with different classification:

— 19 12 11 06* (other wastes (including mixtures of materials) from mechanical treatment of batteries waste containing dangerous substances)

— 19 12 12 07 (other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11*)

However, these waste codes are unspecific and it is not clear for what type of battery or waste fractions these waste codes should be used.

3.4.3. Conclusions on the adaptation of the LoW by Member States

The consultation of the Expert Group on Waste revealed, that

- in Austria all types of batteries are considered as hazardous, without any exception.
- five Member States have already or will soon adapt the LoW to include more detailed entries, in particular for lithium-ion and NiMH batteries;
- the exemption for lithium- and nickel based batteries carried out by some Member States was not done in a harmonised way as these battery wastes are sometimes classified as hazardous and sometimes as non-hazardous. Only one Member State introduced specific national waste codes for intermediate fractions of waste battery recycling but no Member State introduced specific national waste codes for battery manufacturing waste.

4. Results on hazard classification of battery related waste streams and recommendations for new waste codes

This chapter presents the analysis of waste compositions, reviews of the composition for each kind of waste identified, variability in composition and the technical recommendations from JRC based on that evidence to propose a new classification for the List of Waste.

Each section provides an overview of the current state of knowledge on the composition (qualitative and quantitative, including variability) of the battery-relevant wastes under scope. As described in section 2.2.3, the C&L inventory database provided by ECHA (https://echa.europa.eu/information-on-chemicals/cl-inventory-database) was used to link the substances and chemical compounds found in the battery related waste streams to the corresponding hazard statement codes, hazard classes and category codes. The tables in the following sections do also contain the CAS number (Chemical Abstract Service Registry number) and the source (Harmonised C&L[39], REACH registration C&L[40], Notified C&L[41], multiple harmonised classifications[42], or not classified). Only substances with a harmonised classification, as contained in Tables 3.1 and 3.2 of Annex VI to the CLP Regulation have been subject to official scrutiny and the use of this classification and labelling is mandatory. For some substances or chemical compounds, no entry was found in the C&L inventory database (marked as 'not found'). Based on the extensive data base gathered in this investigation, the JRC proposes hazard classifications for the various battery related waste under scope and recommends possible amendments of the EU LoW.

NB. Based on the preliminary remarks (see footnote 4) and the breakdown of waste types considered, it is proposed to amend the name of the main battery-related chapter in the List of Waste, i.e. chapter 16 06, from: "Batteries and accumulators" to: "Wastes from the manufacture, supply and use of batteries"

4.1. Battery manufacturing waste

4.1.1. Lead-acid batteries

Recommendation on classification of battery manufacturing waste from the production of lead-acid batteries and recommendation of new waste codes

No specific information was investigated for lead-acid battery production waste, a well-established industry with operating waste practices. Lead-based batteries contain hazardous substances, and some waste streams from lead-based battery production also have hazardous properties.

Lead-acid batteries are subject to some new obligations under the BWBR, including recycled-content obligations. In order to bring coherence with other battery chemistries, a new waste code for manufacturing waste is proposed for these chemistries as well.

Recommended hazard classification:

The JRC did not receive detailed information on the characteristics of the manufacturing waste from lead-acid battery production. However, lead-based batteries contain hazardous substances in significant quantities leading to their current classification as hazardous. It can therefore be determined that some waste streams from lead-based battery production will display hazardous

[39] Harmonised C&L as included in Tables 3.1 and 3.2 of Annex VI to the CLP Regulation.

[40] In case the source of the classification for a substance is 'REACH registration C&L', a joint entry exists in the C&L database. In this case, a classification comes from a lead dossier of a REACH registration joint submission.

[41] In case the source is 'Notified C&L', various notified classifications may exist for the same notified substance. Generally hazard classifications having the greatest number of notifiers have been used.

[42] Multiple harmonised classifications. Substances having several different harmonised classification, under different index numbers in CLP. For example metallic zinc powder, with different harmonised classifications for pyrophoric and stabilised forms.

properties while others will not. The JRC therefore proposes to classify lead-acid battery manufacturing waste under a mirror entry.

Recommendation for new waste codes for battery manufacturing waste for lead-acid batteries in the LoW:

The JRC proposes to assign the outputs from lead-acid battery manufacturing waste to new waste codes to be added to the existing sub-chapter “16 06” (one hazardous and one non-hazardous):

- 16 06 21* Lead-acid battery manufacturing waste containing hazardous substances (for example lead paste, lead scrap)
- 16 06 22 Lead-acid battery manufacturing waste other than those mentioned in 16 06 21

4.1.2. Lithium-based batteries

Through the stakeholder consultation, the JRC has gained deeper insight into the chemical composition and physical state of certain waste streams originating from battery manufacturing, mainly from NMC lithium battery production. For other types of batteries no data was collected specifically. Stakeholders were asked about specific waste streams, their material composition and amounts of material, their physical state, granularity, chemical composition and other characteristics. The following **Table 5** gives an overview on the characteristics of the waste streams from NMC lithium battery manufacturing. Based on these characteristic certain operators have determined if a manufacturing waste stream should, in their view, be classified as non-hazardous or hazardous. In addition **Table 6** provides the elemental composition of a waste NMC wet cell.

Manufacturers classify a waste stream as hazardous as soon as it contains metal oxide cathode powder (e.g. LiNiMnCo-oxide) and/or electrolytes. Most of these metal oxide cathode powders and electrolytes display hazardous properties. The hazard classification of these compounds is presented in detail in section 4.1.1. In contrast, anode powder (graphite) containing waste streams are classified as non-hazardous.

Table 5. Overview on NMC lithium battery manufacturing waste streams and their chemical and physical characteristics

Manufacturing waste stream (NMC)	Materials	Weight	Physical state	Granularity	Other properties	Hazard classification by manufacturer
Cu-foil (pieces) coated with graphite	Cu, Graphite	N/A*	Solid	Massive	N/A	Non-hazardous
Graphite slurry	Water Graphite	N/A	Aqueous liquid	N/A	N/A	Non-hazardous
Al-foil (pieces) coated with NMC	Al-foil $Ni_xCo_yMn_zLiO_2$ PVDF	N/A	Solid	Massive	N/A	Hazardous
Cathode electrode cut-offs waste	$LiNi_xMn_yCo_{1-x-y}$ Al PVDF Carbon	85 % 13 % 1 % 1 %	Solid	Massive	N/A	N/A
Battery cell waste	$LiNi_xMn_yCo_{1-x-y}$ Graphite EMC (electrolyte) EC (electrolyte) Cu Al $LiPF_6$	39 % 29 % 12 % 7 % 5 % 4 % 4 %	Solid	Massive	Containing solvent	N/A
Anode electrode cut-offs waste	Graphite Cu CMC (electrolyte) Carbon	75 % 22 % 1 % 1 % 1 %	Solid	Massive	N/A	N/A

	SBR[43] (Binder)					
Dry cell waste	$LiNi_xMn_yCo_{1-x-y}$ Graphite Cu Al	45 % 33 % 12 % 10 %	Solid	Massive	N/A	N/A
Cathode slurry	$LiNi_xMnyCo_{1-x-y}$ NMP (electrolyte) PVDF Carbon	65 % 31 % 2 % 2 %	Non-aqueous liquid	Powder	Containing solvent	N/A
Anode slurry	Graphite H_2O CMC (electrolyte) Carbon SBR (Binder)	65 % 32 % 1 % 1 % 1 %	Non-aqueous liquid	Powder	Containing solvent	N/A
NMC powder	$LiNi_xMn_yCo_{1-x-y}$	100 %	Solid	Powder	N/A	Hazardous
Graphite powder	Graphite	100 %	Solid	Powder	N/A	Non-hazardous

*data not available (N/A)

Table 6. Elemental analysis of waste from wet cell production from NMC lithium battery manufacturing

Manufacturing waste stream (NMC)	Materials	Weight	Physical state	Granularity	Other properties
Wet cell	Al C Co Cu Li Mn Ni O Organic solvent (electrolyte) Plastic	5.5 % 29.5 % 5.8 % 7.7 % 3.0 % 6.5 % 11.4 % 6.8 % 14.8 % 9.02 %	Solid	Massive	N/A

Recommendation on classification of battery manufacturing waste from the production of lithium-based batteries and recommendation for new waste codes

The stakeholder consultation revealed that with the exception of the sub-chapters 16 06 and 20 01, the waste codes currently used for lithium battery manufacturing waste belong to chapters that are not specifically related to batteries (see section 3.1.1).

For manufacturing waste, in principle, non-hazardous waste codes are assigned to waste from anode production (e.g. anode electrode cut-offs waste, anode powder, anode slurry, anode foils, coated anode foils). In contrast, waste from cathode production (e.g. cathode electrode cut-offs waste, cathode powder, cathode slurry, coated cathode foils) is allocated to a hazardous waste code.

As soon as a waste stream contains metal oxide cathode powder (e.g. LiNiMnCo-oxide) or electrolytes, the waste stream could be considered to have hazardous properties (see section 2.1.2.1).

Manufacturing waste stream (NMC)	Materials	Weight	Physical state	Granularity	Other properties	Hazard classification by manufacturer
Cu-foil (pieces) coated with graphite	Cu, Graphite	N/A*	Solid	Massive	N/A	Non-hazardous

[43] Styrene Butadiene Rubber

Graphite slurry	Water Graphite	N/A	Aqueous liquid	N/A	N/A	Non-hazardous
Al-foil (pieces) coated with NMC	Al-foil NixCoyMnzLiO2 PVDF	N/A	Solid	Massive	N/A	Hazardous
Cathode electrode cut-offs waste	LiNixMnyCo1-x-y Al PVDF Carbon	85 % 13 % 1 % 1 %	Solid	Massive	N/A	N/A
Battery cell waste	LiNixMnyCo1-x-y Graphite EMC (electrolyte) EC (electrolyte) Cu Al LiPF6	39 % 29 % 12 % 7 % 5 % 4 % 4 %	Solid	Massive	Containing solvent	N/A
Anode electrode cut-offs waste	Graphite Cu CMC (electrolyte) Carbon SBR (Binder)	75 % 22 % 1 % 1 % 1 %	Solid	Massive	N/A	N/A
Dry cell waste	LiNixMnyCo1-x-y Graphite Cu Al	45 % 33 % 12 % 10 %	Solid	Massive	N/A	N/A
Cathode slurry	LiNixMnyCo1-x-y NMP (electrolyte) PVDF Carbon	65 % 31 % 2 % 2 %	Non-aqueous liquid	Powder	Containing solvent	N/A
Anode slurry	Graphite H2O CMC (electrolyte) Carbon SBR (Binder)	65 % 32 % 1 % 1 % 1 %	Non-aqueous liquid	Powder	Containing solvent	N/A
NMC powder	LiNixMnyCo1-x-y	100 %	Solid	Powder	N/A	Hazardous
Graphite powder	Graphite	100 %	Solid	Powder	N/A	Non-hazardous

Table 5 shows, that in cathode electrode cut-offs waste, battery cell waste, dry cell waste, and cathode slurry the concentration of metal oxide powder is in the range of about 40–85 %. **Table 9** shows, that LCO, NMC, LMO and NCA have hazardous statement codes with a very low concentration limit so that a classification as hazardous is necessary. Furthermore, the waste from the cathode production and also the battery cell waste contain or are impregnated with electrolytes. Electrolytes are in many cases flammable liquids (Annex 6, Table 44). If the presence of a substance indicates that the waste is flammable, it should be classified as hazardous by HP 3. With a presence of 19–32 % (battery cell waste and cathode slurry) these waste should generally be classified as hazardous, subject to specific assessment where appropriate and proportionate. Waste streams, mainly from the anode production, do not contain substances that make a classification as hazardous necessary.

Recommended hazard classification:

Based on the information on the currently used waste codes by lithium battery manufacturers and the detailed information on the characteristics for the waste streams received from operators, the JRC proposes to classify the lithium battery manufacturing waste as both non-hazardous and hazardous (mirror entry).

Recommendation for new waste codes for battery manufacturing waste for lithium-based batteries in the LoW:

The JRC proposes to introduce both a non-hazardous and a hazardous waste code for wastes from lithium-based battery manufacturing in sub-chapter: “16 06”

- 16 06 23* Lithium-based battery manufacturing waste containing hazardous substances (for example including cathode electrode cut-offs, waste, cathode slurry)
- 16 06 24 Lithium-based battery manufacturing waste other than those mentioned in 16 06 23 (for example including anode cut-offs)

4.1.3. Nickel-based batteries

Recommendation on classification of battery manufacturing waste from the production of nickel-based batteries and recommendation for new waste codes

The stakeholder consultation revealed that with the exception of the sub-chapters 16 06, the waste codes currently used for nickel battery manufacturing waste belongs to chapters that are not related to batteries (see section 3.1.3). Non-hazardous waste codes are used for a large number of nickel-based battery manufacturing wastes (e.g. battery assembly, ceramic electrolyte production). Hazardous waste codes are applied for waste streams containing liquid and solid cathode material (see section 3.1.3).

The JRC did not receive detailed information on the characteristics of the manufacturing waste from nickel battery production. However, nickel-based batteries contain hazardous substances in significant quantities leading to classification (see section 4.2.3). It can therefore be determined that some waste streams from nickel battery production will display hazardous properties, while others will not.

Recommended hazard classification:

Based on the information on the waste codes currently used by nickel-based battery manufacturers, due to the fact that nickel-based batteries contain both non-hazardous and hazardous substances (and that the waste streams from production also contain these non-hazardous and hazardous substances, which are often found in distinct waste fractions), the JRC proposes to classify nickel-based battery manufacturing waste under a mirror entry.

Recommendation for new waste codes for battery manufacturing waste for nickel-based batteries in the LoW:

The JRC proposes to introduce a new non-hazardous and a hazardous waste code for wastes from nickel-based battery manufacturing in the sub-chapter “16 06” :

- 16 06 25* Nickel-based battery manufacturing waste containing hazardous substances (for example waste streams containing liquid and solid cathode material)
- 16 06 26 Nickel-based battery manufacturing waste other than those mentioned in 16 06 25

4.1.4. Alkaline-based batteries

Recommendation on classification of battery manufacturing waste from the production of alkaline-based batteries and recommendation for new waste codes

The JRC did not receive detailed information on the characteristics of the manufacturing waste from alkaline-based battery production. However, alkaline-based batteries contain hazardous substances in significant quantities leading to their proposed classification (see section 4.2.4). It can therefore be determined that some waste streams from alkaline-based battery production will display hazardous properties while others will not.

Recommended hazard classification:

Based on the information on the waste codes currently used by alkaline-based battery manufacturers, due to the fact that alkaline-based batteries contain both non-hazardous and hazardous substances (and that the waste streams from production also contain these various substances, which are often found in distinct waste fractions), the JRC proposes to classify alkaline-based battery manufacturing waste under a mirror entry.

Recommendation for new waste codes for battery manufacturing waste for alkaline-based batteries in the LoW:

The JRC proposes to introduce two new generic waste codes in sub-chapter “16 06”, one hazardous and one non-hazardous:

- 16 06 27* Alkaline-based battery manufacturing waste containing hazardous substances
- 16 06 28 Alkaline-based battery manufacturing waste other than those mentioned in 16 06 27

4.1.5. Zinc-based batteries

Recommendation on classification of battery manufacturing waste from the production of zinc-based batteries and recommendation for new waste codes

The JRC did not receive detailed information on the characteristics of the manufacturing waste from zinc-based battery production. However, zinc-based batteries contain hazardous substances in significant quantities leading to classification (see section 4.2.5). It can therefore be determined that some waste streams from zinc-based battery production will display hazardous properties while others will not.

Recommended hazard classification:

Based on the information on the waste codes currently used by zinc-based battery manufacturers, due to the fact that zinc-based batteries contain both non-hazardous and hazardous substances (and that the waste streams from production also contain these various substances, which are often found in distinct waste fractions), the JRC proposes to classify zinc-based battery manufacturing waste under a mirror entry.

Recommendation for new waste codes for battery manufacturing waste for zinc-based batteries in the LoW:

The JRC proposes to assign the outputs from zinc-based battery manufacturing waste to the new generic waste codes in the sub-chapter “16 06” (one hazardous and one non-hazardous):

- 16 06 29* Zinc-based battery manufacturing waste containing hazardous substances
- 16 06 30 Zinc-based battery manufacturing waste other than those mentioned in 16 06 29

4.1.6. Sodium-based and other batteries

Recommendation on classification of battery manufacturing waste from the production of sodium-based batteries and recommendation for new waste codes

No information is available yet for sodium-based battery production waste, a relatively novel battery chemistry. Sodium-based batteries contain hazardous substances (see section 4.1.6). It can therefore be assumed that waste streams from sodium battery production also have hazardous properties.

Recommended hazard classification:

Due to the fact that sodium-based batteries contain both hazardous and non-hazardous substances and that the waste streams from productions contain these substances as well, the JRC proposes to classify sodium battery manufacturing waste under a mirror entry.

Recommendation for new waste codes for battery manufacturing waste for sodium-based batteries in the LoW:

Even though no data is available, the JRC proposes to assign the outputs from sodium-based battery manufacturing waste to the new generic waste codes in sub-chapter "16 06" (one hazardous and one non-hazardous):

- 16 06 31* Sodium-based battery manufacturing waste containing hazardous substances
- 16 06 32 Sodium-based battery manufacturing waste other than those mentioned in 16 06 31

NB. Future battery chemistries with no commercial or industrial relevance at the time of establishment of the present nomenclature will also use the above waste codes for the identification of battery manufacturing waste.

4.1.7. Other batteries

For battery chemistries that are not covered in this study, the JRC proposes the follows.

Recommendation for new waste codes for battery manufacturing waste for other batteries in the LoW:

For other battery chemistries, the JRC proposes to assign the wastes occurring from battery manufacturing to the new generic waste codes in sub-chapter "16 06" (one hazardous and one non-hazardous):

- 16 06 33* Battery manufacturing waste containing hazardous substances other than those mentioned in 16 06 21, 16 06 23, 16 06 25, 16 06 27, 16 06 29 and 16 06 31.
- 16 06 34 Battery manufacturing waste other than those mentioned in 16 06 22, 16 06 24, 16 06 26, 16 06 28, 16 06 30 and 16 06 32

4.2. Waste batteries

4.2.1. Waste lithium-based batteries containing liquid electrolyte

A single lithium battery cell generally consists of the components presented in **Table 7**. **Table 7** shows the weight of the different components related to the total battery. Detailed background information on the chemical composition on waste lithium-based batteries is provided in Annex 4 (**Table 42**). The literature research performed by the JRC revealed a great variability of certain components, even within the same battery chemistry (Accardo et al., 2021; Golubkov et al., 2014; Latini et al., 2022; Sobianowska-Turek et al., 2021). Depending on the purpose of the battery in the drive system of a car (e.g. hybrid electric, plug-in hybrid electric vehicle, plug-in hybrid electric vehicle or battery electric vehicles) the amount of cathode material (e.g. NMC) can vary between 19 % (hybrid electro) to 39 % (battery electric vehicle) (Winjobi et al. 2021).

Table 7. Variability of the main battery components for the different lithium-based battery chemistries under scope

Battery component	Component/s	LCO, LMO, NMC[44], NCA	LTO	LFP
		Weight (% total battery)		
Cathode material	Metal salts, other lithium compounds	20–50 %	20–50 %	20–50 %
Cathode current collector	Aluminium foil	8–15 %	6–8 %	6–8 %

[44] In the cathode and anode, NMC batteries contain carbon nanotubes (CNT) with a share of 0.1–2 %.

Anode material	Graphite, Silicon dioxide, Carbon black	10–30 %	10–30 %	10–20 %
Anode current collector	Copper foil	7 %	10–12 %	10–20 %
Electrolyte	Lithium salts, Organic solvents	10–20 % (thereof 1–3 % lithium salts)	10–20 % (thereof 1–3 % lithium salts)	10–20 % (thereof 1–3 % lithium salts)
Binder	e.g. PVDF	1–8 %	1–8 %	0.5–1 %
Separator	Polymeric membranes (e.g. PE or PP), Non-woven fabric mats, Styrene Butadiene Rubber (SBR)	3–5 %	3–5 %	3–5 %
Case and tab	Steel, plastic	15–30 %	15–30 %	15–30 %

The composition of Lithium Thionyl Chloride batteries differs from the other lithium-based batteries presented in **Table 7** and are therefore presented separately in the following **Table 8**.

Table 8. Main components in Lithium Thionyl Chloride batteries.

Battery component	Chemical compound	Weight (% total battery)
Cathode material	$SOCl_2$	18–47 %
	SO_2Cl_2	30–45 %
	$AlCl_3$	1–5 %
Cathode current collector	unknown	Unknown
Anode material	Carbon black	2–6 %
	LiMe	2–6 %
	$GaCl_4$	0–2 %
Anode current collector	unknown	Unknown
Electrolyte	LiCl	1–2 %
Binder	PTFE	0–1 %
Case and tab	unknown	Unknown

In the following sections, the different battery components namely cathode material, anode material, electrolyte, binder and separator are assessed regarding their content of hazardous substances and consequently also as regards their hazard classification. Cathode current collector (aluminium: CAS 7429-90-5, not classified), anode material (graphite: CAS 7782-42-5, not classified; silicon dioxide:

CAS 14808-60-7, not classified; carbon black: CAS 1333-86-4, not classified), anode current collector (copper in massive form: no CL inventory entry) as well as case and tab (steel: CAS 12597-69-2, not classified) consists of components that are not classified as hazardous, and therefore do not need to be explicitly assessed in this work.

Cathode material

For each cathode material entries exist in the CL data inventory. **Table 9** shows, that the concentration of LCO, NMC, LMA and NCA are present in batteries in such concentration that the corresponding limit concentration are exceeded and would result in a hazardous classification. For the Lithium Thionyl Chloride batteries, the concentration of the cathode materials is as well present in such concentration, that a hazardous classification would be necessary (Annex 5, **Table 43**). In comparison for LTO and LFP, the substances are not classified and no hazardous classification arises from these two chemical compound (**Table 9**).

Anode material

The anode material mainly consists of graphite, silicon dioxide, and carbon black. No hazardousness is defined for these substances (Table 9 and (Annex 5, Table 43).

Table 9. Overview on cathode materials for different commercial lithium battery composition with hazard identification according to CLP (1272/2008)

Battery chemistry	Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. Limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
LCO	$LiCoO_2$	20–50 %	12190-79-3	REACH registration C&L	H360Fd	Repr. 1B	≥ 0.3 %	Y	HP 10
NMC	$LiNi_xMn_yCo_zO_2$[45]		various CL entries considering the elemental composition[46]	Notified C&L	H317 H330 H334 H350 H360 H372 H412	Skin Sens. 1 fatal if inhaled Resp. Sens. 1 Carc. 1A Repr. 1B STOT RE 1 Aquatic Chronic 3	≥ 10 % ≥ 0.1 % ≥ 10 % ≥ 0.1 % ≥ 0.3 % ≥ 1 % ≥ 25 %	Y Y Y Y Y Y °Y	HP 13 HP 6 HP 13 HP 7 HP 10 HP 5 HP 14
LMO	$Li_xMn_yO_4$		12057-17-9	Notified C&L	H302 H332 H413	Acute Tox. 4 Acute Tox. 4 Aquatic Chronic 4	≥ 25 % ≥ 22.5 % ≥ 25 %	°Y °Y °Y	HP 6 HP 6 HP 14
NCA	$LiNi_xCo_yAl_zO_2$		177997-13-6; 193214-24-3	REACH registration C&L; Notified C&L	H314 H317 H318	Skin Corr. 1B Skin Sens. 1 Eye Dam. 1	≥ 5 % ≥ 10 % ≥ 10 %	Y Y Y	HP 8 HP 13 HP 14

[45] The basic formula of NMC consists of 33 % Ni, 33 % Mn, and 33 % Co ($LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$, NMC 111), but the share of the metals can vary in different NMC. Typically used blends are $LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$ (NCM 424), $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ (NCM 523), $LiNi_{0.5}Co_{0.3}Mn_{0.2}O2$ (NCM 532), $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ (NCM 622), and $LiNi_{0.8}Co_{0.1}Mn_{0.1}O2$ (NCM 811).

[46] CAS No.: 113066-89-0: Lithium Nickel Cobalt Oxide ($LiNi_{0.8}Co_{0.2}O_2$) - Notified C&L; CAS No.: 12031-65-1: Lithium Nickel Cobalt Aluminium Oxide (no specific composition given) - Harmonised C&L; CAS No.: 131344-56-4: Cobalt Lithium Nickel Oxide (no specific composition given) - Harmonised C&L; CAS No.: 13977-83-8: Li-, Ni(II)-, P - Notified C&L; CAS No.: 179802-95-0: Lithium Nickel Manganese Cobalt Oxide (composition: $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) - Notified C&L; CAS No.: 182442-95-1: Cobalt Lithium Manganese Nickel Oxide (no specific composition given) - Notified C&L; CAS No.: No CAS number, but EC No. 480-390-0: Cobalt Lithium Manganese Nickel Oxide (no specific composition given) - REACH registration C&L; CAS No.: 193215-05-3: Lithium Nickel Manganese Cobalt Oxide ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$) - Notified C&L; CAS No.: 193215-53-1: Lithium Nickel Manganese Cobalt Oxide ($LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$) - Notified C&L; CAS No.: 193215-96-2: Lithium Nickel Manganese Cobalt Oxide ($LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$) - Notified C&L; CAS No.: 193214-24-3: Lithium Nickel Cobalt Aluminium Oxide (no specific composition given) - Notified C&L; CAS No.: 346417-97-8: Cobalt Lithium Manganese Nickel Oxide (no specific composition given) - Notified C&L;

					H330 H334 H350 H360 H372 H412	Acute Tox. 2 Resp. Sens. 1 Carc. 1A Repr. 1B STOT RE 1 (lungs) Aquatic Chronic 3	≥ 0.1 % ≥ 10 % ≥ 0.1 % ≥ 0.3 % ≥ 1 % ≥ 25 %	Y Y Y Y Y °Y	HP 6 HP 13 HP 7 HP 10 HP 5 HP 14
LTO	Li_2TiO_3		12031-82-2	REACH registration C&L	-	not classified	-	-	-
LFP	$LiFePO_4$, Phosphoric acid, iron($^{2+}$) lithium salt (1:1:1) ($FeLiO_4P$)	20–50 %	15365-14-7 1199808-36-0	Notified C&L REACH registration C&L	- -	not classified not classified	- -	- -	- -

Electrolytes

Lithium-based batteries as e.g. **LCO, LMO, NMC, NCA and LTO** contain organic electrolytes, usually in the form of lithium salts dissolved in a mixture of organic solvents (liquid electrolytes) in concentrations of 10–20 %. Lithium salts make up only a small proportion of this (1–3 % of the total battery). The most commonly used lithium salts are $LiPF_6$, $LiBF_4$ and $LiClO_4$. Commonly used organic solvents include ethylene-, propylene-, or dimethyl carbonates. The essential components of the lithium iron phosphate batteries **(LFP)** are identical to the electrolytes of other lithium-based batteries (Das et al., 2023; Sobianowska-Turek et al., 2021; Zackrisson and Schellenberger, 2020). In LFP, most commonly used organic solvents are DMC, EMC, DEC and EC and $LiPF_6$ and LiFSl are the most commonly used lithium salts (RECHARGE, 2024)

An extensive overview on liquid electrolytes present in lithium-based batteries, along with attributed hazards is given in Annex 6 (Table 44).

Even though complex lithium salts are present in lithium-based batteries only in low concentration, these chemical components, in particular lithium salts containing cobalt and/or nickel are classified in their registration dossiers as toxic for reproduction (Repro 1B) or as carcinogenic (Carc 1A) that result in the waste being assigned a hazardous classification even when these substances are present at low concentrations.

Several organic solvents are flammable or even highly flammable (e.g. EMC, DC, DMC, TFT, DEC). The hazardous statement assigned to these organic solvents are H225 (Flam. Liq. 2) and H226 (Flam. Liq. 3). Due to the high concentration (10–20 %) and the characteristics of the organic solvents, all organic solvents trigger a hazardous classification and/or are (highly) flammable.

Binder

One of the most widely used binders in lithium-based batteries is polyvinylidene fluoride (PVDF). This binder dissolves usually in an organic solvent such as N-methyl-2-pyrrolidone (NMP). Carboxy methyl cellulose (CMC) is another well-known binder in an aqueous solvent (Das et al., 2023). Further known are Na-alginate, polyacrylic latex (LA132), Poly(acrylic acid) (PPA), poly(diallyldimethylammonium) (PDADMA) that are all applied in an aqueous solvent.

Certain Per- and Polyfluorinated Substances (PFAS) are claimed to be essential parts of lithium-based batteries (Gao et al., 2024), although PFAS-free lithium-based batteries are already available on the market (Buqa and Carpentier, 2024). According to (RECHARGE, 2023) among PFAS, only **fluoropolymers** are used in the binders used in the battery industry. More specifically, fluorinated binders offer a higher stability due to their resistance to oxidation compared to non-fluorinated binders. These binders can also prevent self-discharge by inhibiting some electrochemical reactions and thus improve the energy density as well as lifespan of the battery. The use of fluoropolymers may be divided in two main categories:

- Use in binder at electrode level: **PVDF (polyvinylidene fluoride)** and **PTFE (polytetrafluoroethylene)**
- Other uses at cell/battery level (Kellermann and Metz, 2023; RECHARGE, 2021):
  - **FEP (fluorinated ethylene propylene)** and **PTFE** for separator coatings, additives in the electrolyte, gaskets/seals, pipes, valves and sealing for instance.
  - **FEC (fluoroethylene carbonate)** electrolyte additive that increases the cycling performance rate capability and lowers the initial irreversible capacity loss of lithium-based batteries by facilitating the formation of stable solid electrolyte interface (SEI) films on the surface of the cathode active material (Li et al., 2015).
  - **LiTFSI** (Lithium bis(trifluoromethylsulfonyl)amide) and **F-EPE** (Fluorinated ethylene propylene) used as additives in the electrolyte.

For the production of an electrolyte, PVDF is mixed with organic solvents such as **N-Methyl-2-pyrrolidone (NMP)** and other electrode components[47]. The produced wet mix is coated on a metallic foil and then heated below the degradation temperature of PVDF. The dried electrode is then used to manufacture a cell. NMP is listed in the CL inventory under CAS No. 872-50-4 and the following Hazard statements are given (H315 (Skin Irrit. 2), H319 (Eye Irrit. 2), H335 (STOT SE 3) and H360D (Repr. 1B); Harmonised C&L).

In case of PTFE, a PTFE dispersion is mixed with electrode components and carbon black. This wet mix is also processed and heated below the degradation temperature of the PTFE and the dried electrolyte is then further used for cell manufacturing.

In their review study, (Rensmo et al., 2023) listed around 20 fluorinated substances found in lithium battery components. The list with the hazard identification of the fluorinated substances according to CLP (1272/2008) is given in Annex 7 (**Table 45**).

Table 10 gives an overview on the binders used in lithium-based batteries and their hazard classification.

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[47] NMP is subject to a restriction under Annex XVII of REACH (entry 71), which requires users to implement specific risk management measures

Table 10. Binders used in lithium-based batteries, with hazard identification according to CLP (Regulation (EC) No. 1272/2008)

Chemical compound		Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
PVDF	Polyvinylidene fluoride	1–8 %	24937-79-9	Notified C&L	-	not classified	-	-	-
					H315 H319 H335	Skin Irrit. 2 Eye Irrit. 2 STOT SE 3	≥ 20 % ≥ 20 % ≥ 20 %	N N N	HP4 HP4 HP5
PTFE	Polytetrafluoroethylene		9002-84-0	Notified C&L	-	not classified	-	-	-
NMP	N-methyl-2-pyrrolidone		872-50-4	Harmonised C&L	H315 H319 H335 H360D	Skin Irrit. 2 Eye Irrit. 2 STOT SE 3 Repr. 1B	≥ 20 % ≥ 20 % ≥ 20 % ≥ 0.3 %	N N N Y	HP4 HP4 HP5 HP10
LA132	Na-alginate, polyacrylic latex		9003-04-7	Notified C&L	-	not classified	-	-	-
					H319	Eye Irrit 2.	≥ 20 %	N	HP4
PPA	Poly(acrylic) acid		9003-01-4	Notified C&L	-	not classified	-	-	-
				REACH registration C&L	H302 H318 H335 H412	Acute Tox. 4 Eve Dam. 1 STOT SE 3 Aquatic Chronic 3	≥ 25 % ≥ 10 % ≥ 20 % ≥ 25 %	N N N N	HP6 HP4 HP5 HP14
PDADM	Poly(diallyldimethylammonium))		26062-73-3	Notified C&L	H412	Aquatic Chronic 3	≥ 25 %	N	HP14

Reactions during lithium-based battery life time and end-of-life processing

Electrochemical processes during the use of lithium-based batteries might also cause the formation of new chemical compounds e.g. in the electrolyte. The electrolyte dissociates into lithium fluoride (LiF) and phosphorus pentafluoride (PF_5), which reacts with moisture and forms hydrogen fluoride (HF) and phosphoryl fluoride (OPF_3). HF can represent a high environmental and health risks due to the high acute toxicity, e.g. in case of cell damage (leakage) or during end-of-life processing (Weber et al., 2014; Zackrisson and Schellenberger, 2020).

Equation 1 $LiPF_6 \text{ (s)} \rightleftharpoons LiF \text{ (s)} + PF_5 \text{ (g)}$

Equation 2 $LiPF_6 + H_2O \rightleftharpoons LiF + 2HF + POF_3$

Equation 3 $PF_5 + H_2O \rightleftharpoons 2HF + POF_3$

PVDF and PTFE do not decompose or break down into other PFAS or by-products at the shredding or metal recycling processes. $LiPF_6$ does not generate PFAS from subsequent reactions with the compounds present in the leach solution. In the shredding process, electrolyte salts decompose to lithium hydroxide (LiOH), an insoluble solid compound that locks up the fluorine. Those are then captured in the black mass and further processed.

Table 11. Chemical compounds that are formed during electrochemical processes in lithium-based batteries containing $LiPF_6$ or PF_5 with hazard identification according to CLP (1272/2008)

Chemical compound		CAS No.	Source	Hazard statement code, hazard class and category code	
LIF	Lithium fluoride	7789-24-4	REACH registration C&L	H302 H319	Acute Tox. 4 Eye Irrit. 2
PF_5	Phosphorus pentafluoride	7647-19-0	Notified C&L	H280 H314 H330	Press. Gas (Liq.) Skin Corr. 1A Acute Tox. 2
HF	Hydrogen fluoride	7664-39-3	Multiple harmonised classifications	H300 H310 H314 H330	Acute Tox. 2 Acute Tox. 1 Skin Corr. 1A Acute Tox. 2
POF_3	Phosphoryl fluoride	-	not found	-	-
LiOH	Lithium hydroxide	1310-65-2	REACH registration C&L	H302 H314 H318	Acute Tox. 4 Skin Corr. 1B Eye Dam. 1

In Li-$SOCl_2$ batteries the following electrochemical processes occur and the following chemical compounds are formed (SDS Saft):

- Hydrogen (H_2) as well as lithium oxide (Li_2O) and lithium hydroxide (LiOH) dust are produced in case of reaction of lithium metal with water (hydrolysis).
- Chlorine (Cl_2), sulphur dioxide (SO_2) and disulphur dichloride (S_2Cl_2) are produced in case of thermal decomposition of thionyl dichloride ($SOCl_2$) above 100°C.

- Hydrochloric acid (HCl) and sulphur dioxide (SO_2) are produced in case of reaction of thionyl dichloride ($SOCl_2$) with water at room temperature.
- Hydrochloric acid (HCl) fumes, lithium oxide (Li_2O), lithium hydroxide (LiOH) and aluminium hydroxide ($Al(OH)_3$) dust are produced in case of reaction of lithium tetrachloroaluminate ($LiAlCl_4$) with water.

A detailed table containing the chemical compounds that are formed during the electrochemical processes in Li-$SOCL_2$ with hazard identification is presented in Annex 8 (**Table 46**).

Risk of fire and reactions at incomplete combustion

During battery use, the anode, cathode and the electrolyte will produce electrochemical or chemical reactions and can release heat. Over time, dendrite formation can also pierce the electrolyte and cause a short circuit. In case of short circuit, elevated temperatures, impact and other abuse, thermal runaway can occur (Si et al., 2018). The rapid release of energy leads to the combustion of the electrolyte and, further on, other battery components. In case the battery cell breaks, lithium compounds react with the air causing an intense oxidation that promotes fire or even explosions that are difficult to extinguish.

Incomplete combustion of cathode materials such as fluoropolymer or fluorinated ingredients in the electrolyte can lead to the formation of various persistent perfluorinated alkylated substances (PFAS). So far, the reactions are not completely understood. Potential reaction products of the thermolysis of fluoropolymer binder are:

— Short and long chain perfluoroalkyl acids (PFAA); some of them are POP and PBT substances. The formation will depend on the used electrode binder material (PVDF or FEP)

— Fluorinated gasses such as perfluorinated methane (CF_4)

Recommendation on classification of lithium-based waste batteries with liquid electrolyte and recommendation for new waste codes

This section summarises the arguments for a proposal of a non-hazardous or hazardous classification for the lithium-based batteries under scope and proposes new waste codes for lithium-based waste batteries.

Cathode material:

The metal oxides LCO, NMC, LMO and NCA batteries account for 20–50 % of the battery mass and consist of substances with various hazardous statement codes. Due to the high concentration, the concentration limits for various hazardous statement codes are exceeded, resulting in a hazardous classification[48] (**Table 9**) (EC, 2018). Li-$SOCl_2$ batteries contain $SOCl_2$ (Thionyl chloride) but other chemical compounds in concentration that also result in a hazardous classification. In comparison, the metal oxides LTO and LFP are not classified and therefore are not hazardous.

Electrolytes (lithium salts):

Exemplarily, lithium hexafluorophosphate ($LiPF_6$) is used in many lithium-based batteries (1-3 %) and is classified with the hazard statement code H372 (STOT RE 1) that causes damage to organs through prolonged or repeated exposure. The concentration limit of the individual substance for the waste **to be classified as hazardous HP 5 (Specific Target Organ Toxicity (STOT) / Aspiration Toxicity) is ≥ 1 %** (EC, 2018)**.** In lithium-based batteries, it is highly certain that the content of $LiPF_6$ is **≥ 1 %.**

[48] As described in section 2.2.3, Step 3 of the hazardous determination, concentration limits have been assigned for the hazardous properties HP4 – HP8, HP10, HP11, HP13, and HP14. A waste needs to be classified as hazardous if the concentration limits are equalled or exceeded. As the NMC and NCA batteries exceed the limit value considerably, these lithium waste batteries are classified as absolute hazardous

Besides $LiPF_6$ also the lithium salt lithium tetrafluoroborate ($LiBF_4$) is used in the electrolytes. This battery compound is classified with the hazardous statement code H341 (Mutagenic 2). The concentration limit of the individual substance for the waste to be classified as hazardous is ≥ 1 % and it is **highly likely that in case $LiBF_4$ is used, the content is higher than ≥ 1 %.**

Electrolytes (organic solvents): With the exception of Li-$SOCl_2$ batteries, all other lithium-based batteries contain several organic solvents that are (highly) flammable. Furthermore, due to the high concentration of organic solvents (10–20 %) and their characteristics a hazardous classification is triggered for all lithium-based batteries except Li-$SOCl_2$ batteries.

Fire hazard:

Several condition can lead to lithium ion batteries catching fire (e.g. physical abuse, electrochemical or chemical reactions that cause short-circuiting). In case of a short circuit elevated temperatures and a thermal runaway can occur. In case the battery cell breaks, lithium compounds react with the air causing an intense oxidation that promotes fire or even explosions that are difficult to extinguish. The flammable organic solvents additionally promote the fire.

Formation of new chemical compounds:

Electrochemical processes during the use of lithium-based batteries cause the formation of new chemical compounds with certain hazardous statement code. However, there is currently insufficient information on concentrations of these chemical compounds in a waste battery. Consequently, it is not possible to classify the hazardousness of this newly formed compound to date.

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition and its variability (mainly the cathode material and electrolytes), the classification of the chemical compounds contained, the reactions in the batteries during life-time, the potential risk of fire and the formation of new potentially hazardous substances, the JRC proposes to classify all liquid-electrolyte lithium-based waste batteries as absolute hazardous.

Recommendation for new waste codes for waste lithium-based batteries with liquid electrolyte in the LoW

Based on the approach to the extension of the LoW in Spain (see **Table 3**), the JRC proposes to introduce new absolute hazardous waste codes for waste lithium-based batteries in the existing sub-chapters "16 06" and "20 01 Separate collected fraction (except 15 01)", the sub-chapter of chapter 20, municipal waste:

- 16 06 08* Waste lithium-based batteries
- 20 01 33* Waste batteries included in categories 16 06 01 to 16 06 04, 16 06 07 to 16 06 11, 16 06 13 and unsorted waste batteries containing those waste batteries

4.2.2. Waste lithium-based batteries containing solid electrolyte

The anode of a solid state battery (SSB) is made of graphite, silicon, lithium titanate (LTO) or lithium metal anode (LMA). The cathode material is the same as for lithium-based batteries with liquid electrolyte (see section 4.2.1) and consists of the following metal oxides: NMC, NCA, LCO, LMNO, or LFP. For the cathode, the use of sulphur or iron sulphide (FeS_2) is also possible. The current collector metals are the same as for lithium ion and lithium iron phosphate batteries (cathode: Al; anode: Cu).

In comparison to the batteries described in section 4.2.1, the electrolyte is solid in the solid state batteries. Three main groups of solid electrolyte materials have received the most attention, namely oxides, sulphides and polymer. Oxide solid electrolytes consist of numerous diverse materials and all containing lithium and oxygen as the main components, but also various other elements as rare earth such as Ga, La, or Sc. Sulphide solid electrolyte group consists of numerous diverse materials, all containing lithium and sulphur as the main components as well as other elements, such as P, Si, or

Ge. The group of argyrodites seems especially promising for application in SSB (Batzer et al., 2023; Fraunhofer, 2022; Jean-Fulcrand et al., 2023; Kononova et al., 2023; LaCoste et al., 2021; Wang et al., 2020). Solid electrolytes are for example lithium phosphorous oxynitride (LiPON), lithium garnet (e.g. $Li_7La_3Zr_2O_{12}$), sodium superionic conductor (e.g. $Na_3Zr_2Si_2PO_{12}$, sulphide-based electrolytes (e.g. $Li_{10}GeP_2S_{12}$), polymer-based electrolytes such as polyethylene oxide (PEO) or polyvinylidene fluoride (PVDF) (Abbas et al., 2021) (**Table 12**).

Table 12. Overview on the battery components of solid state lithium-based batteries

Battery component	Chemical compounds
Cathode material	Metal oxides: NMC, NCA, LCO, LMNO Lithium iron phosphate: LFP Sulphur: Sulphur or iron sulphide (FeS_2)
Cathode current collector	Aluminium
Anode material	Graphite Silicon dioxide Lithium titanate (LTO, $Li_4Ti_5O_{12}$) Lithium metal anode (LMA).
Anode current collector	Copper
Electrolyte	Oxide electrolyte:[49] - LiPON type: Lithium phosphorus oxynitride ($Li_{3.3}PO_{3.9}N_{0.17}$) - NASICON-type oxides LATP ($Li_{1+x}A_xTi_{2-x}(PO_4)^3$– LATP with A = Al, Cr, Ga, Fe, In, La, Sc and Y) - Garnet-type: $Li_7La_3Zr_2O_{12}$ (LLZO) - Perovskite-type: $La_{0.51}Li_{0.34}TiO_{2.94}$) Sulphide electrolyte: – LPS sub-class – Thio-LISICONs ($Li_{3.25}Ge_{0.25}P_{0.75}S_4$) – LGPS sub-class: $Li_{10}GeP_2S_{12}$ or $Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$ – Argyrodites: Li_6PS_5Cl or $Li_{5.5}PS_{4.5}Cl_{1.5}$ Polymer electrolyte: – Polymer Matrix (Poly(ethylene oxide) (PEO), Polyethylene carbonate (PEO-EC); Poly(propylene carbonate) (PPC); Polycaprolactone (PCL); Poly(trimethylene carbonate) (PTMC), Succinonitrile (SN), Poly(acrylonitrile) (PAN), Polysiloxane; – Poly[bis(methoxy-ethoxy-ethoxy)phosphazene] (MEEP) – Lithium salt: $LiBF_4$, $LiPF_6$, $LiClO_4$, $LiAsF_6$, $LiN(CF_3SO_2)_2$, CH_3SO_3Li, $LiN(SO_2C_2F_5)_2$, LiC_2F_5SO – Additives: Al_2O_3, SiO_2, TiO_2, ZrO_2, γ-$LiAlO_2$, Li_3N, LiAlO, PyrxTFSI
Separator	Solid electrolytes act as separator
Case and tab	Steel, plastic

[49] These electrolytes are also suitable for use as a separator.

Table 13. Exemplary chemical compounds in solid state lithium-based batteries with hazard identification according to CLP (1272/2008)

Battery chemistry	Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Cathode material	NMC, NCA, LCO, LMNO, LFP	see **Table 9**							
	Sulphur	unknown	7704-34-9	Harmonised C&L	H315	Skin Irrit. 2	> 20 %	-	-
	FeS_2	unknown	1317-37-9	REACH registration C&L	-	not classified	-	-	-
Anode material	LTO, LMA	see **Table 9**							
Electrolyte	LiPON	unknown	not found	-	-	-	-	-	-
	$Li_7La_3Zr_2O_{12}$	unknown	not found	-	H314 H335	Skin Corr. 1A STOT SE 3	≥ 1 % and < 5 % > 20 %	-	-
	$Na_3Zr_2Si_2PO_{12}$	unknown	58572-20-6	Notified C&L	H302 H312 H315 H317 H319 H332 H335	Acute Tox. 4 Acute Tox. 4 Skin Irrit. 2 Skin Sens. 1 Eye Irrit. 2 Acute Tox. 4 STOT SE 3	≥ 25 % ≥ 55 % > 20 % ≥ 10 % ≥ 20 % ≥ 22.5 % > 20 %	-	-
	$Li_{10}GeP_2S_{12}$	unknown	1333081-96-1[50]	not found	-	-	-	-	-
	PEO	unknown	25322-68-3	REACH registration C&L	not classified	-	-	-	-

[50] CAS number available for $Li_{10}GeP_2S_{12}$ but no entry found in CL inventory

Risk of fire

In contrast to lithium-based batteries with a liquid electrolyte, solid-state batteries tolerate higher temperatures and have a higher thermal stability, which makes them safer. Furthermore, these solid state batteries do not contain (highly) flammable organic solvents. A first non-exhaustive review on the solid electrolytes revealed, that most of them have different hazard statement code, but without the knowledge on their percent share within a battery, a hazard classification is not possible.

Recommendation on classification of lithium-based waste batteries with solid electrolyte and recommendation for new waste codes

As solid state batteries are not yet manufactured and used on a large scale, too little is currently known about their exact qualitative and quantitative composition, let alone their variability. However, it is known that the same anode and cathode material (e.g. metal oxides) are used in solid state batteries as they are used in lithium ion batteries.

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition and its variability, the classification of the chemical compounds contained, the reactions in the batteries during life-time and the potential risk of fire and the formation of new potentially hazardous substances the JRC proposes to **classify all solid state waste lithium-based batteries as absolute hazardous.**

Recommendation for new waste codes for solid state waste lithium-based batteries in the LoW:

The JRC proposes to assign the solid state waste lithium-based batteries to the same absolute hazardous waste codes that were defined in section 4.2.1 for waste lithium-based batteries containing liquid electrolytes.

- 16 06 08* Waste lithium-based batteries
- 20 01 33* Waste batteries included in categories 16 06 01 to 16 06 04, 16 06 07 to 16 06 11, 16 06 13 and unsorted waste batteries containing those waste batteries

Therefore, to summarise the above classifications, **the JRC proposes to classify all waste lithium-based batteries as absolute hazardous** under single waste codes (for liquid and solid electrolyte batteries, also encompassing lithium-ion and lithium-metal chemistries).

4.2.3. Waste nickel-based batteries

Nickel-Metal-Hydride batteries

The chemical reaction at the positive electrode of a NiMH battery is similar to that of the nickel–cadmium (Ni-Cd) cell. However, in comparison to the Ni-Cd battery, the NiMH battery uses a hydrogen absorbing alloy instead of the toxic cadmium at the anode. The cathode in commercial NiMH consists of nickel $Ni(OH_2)$ when the battery is discharged. Nickel-oxide-hydroxide (NiO(OH)) is present in the charged state of the battery (Zhang and Revathi, 2016) (see section 4.1.3). The anode is based on a metal hydride alloy that allows the absorption of reaction product hydrogen. For the storage of the produced hydrogen, so far only a small number of metal alloys, including AB_5-type or AB_2-type alloys have been developed (Ouyang et al., 2017). These alloys consist of various rare earths such as lanthanum, cerium, neodymium, or praseodymium (AB5 alloys: $La_{5.7}Ce_{8.0}Pr_{0.8}Nd_{2.3}Ni_{59.2}Co_{12.2}Mn_{6.8}Al_{5.2}$ or $La_{10.5}Ce_{4.3}Pr_{0.5}Nd_{1.3}Ni_{60.1}Co_{12.7}Mn_{5.9}Al_{4.7}$; AB2 alloy: $V_{18}Ti_{15}Zr_{18}Ni_{29}Cr_5Co_7Mn_8$, $V_5Ti_9Zr_{26.7}Ni_{38}Cr_5Mn_{16}Sn_{0.3}$, or $V_5Ti_9Zr_{26.2}Ni_{38}Cr_{3.5}Co_{1.5}Mn_{15.6}Al_{0.4}Sn_{0.8}$).

Taking into account only the rare earths, their content in a NIMH battery can be in the range of 5-15 %. Commonly potassium hydroxide (KOH) is used as an electrolyte, whereas sodium hydroxide (NaOH) is an alternative alkaline electrolyte. The separator is made of nonwovens (polymers). The data for the mass fraction of the individual components in NiMH batteries originates mainly from safety data sheets from EKF Diagnostik, Motorola, Tenergy, Staples, Ermatet, Umicore and Energizer (Al-Thyabat et al., 2013).

Table 14. Battery components of NiMH, their chemical compounds and the % share on the total battery mass

Battery component	NiMH	
	Compound	Weight (% total battery)
Cathode	$Ni(OH)_2$ (discharged state) NiO(OH) (charged state)	25–45 %
Cathode plate	Ni foam	no data
Anode	Metal hydride alloy to e. g. AB5 (rare-earth mixture of A is lanthanum, cerium, neodymium, praseodymium, and B is nickel, cobalt, manganese, or aluminium (e.g. $La_{0.8}Nd_{0.2}Ni_{2.5}Co_{2.4}Si_{0.1}$)	20–40%
Anode plate/foil	Ni plated steel	no data
Electrolyte	KOH, NaOH	5–15 %
Separator	Polyolefin	5 %
Other	-	-
Case and tab	Steel, plastic	25–30 %

Chemical compounds of NiMH batteries and their hazardous properties

The following table presents examples of the chemical compounds used in NiMH batteries, along with their CAS numbers, hazard statement/hazard class and category codes, concentration limit for hazard classification, indication if the concentration limit is exceeded and the associated hazardous properties (HP) related to a hazard statement code. For certain substances as e.g. metal hydride alloy (AB5) no entries were found in the C&L inventory. However, the AB5 consists of various elements as e.g. nickel, cobalt, manganese, or aluminium for which entries exist.

Table 15. Selected chemical compounds of NiMH batteries with hazard identification according to CLP (1272/2008)

Battery component	Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz.Class. (Y/N/°)	H (WFD Annex III)
Cathode	$Ni(OH)_2$	15–25 %	12054-48-7	Harmonised C&L	H302 H315 H317 H332 H334 H341 H372 H400 H410 H350i H360D	Acute Tox. 4 Skin Irrit. 2 Skin Sens. 1 Acute Tox. 4 Resp. Sens. 1 Muta. 2 STOT RE 1 Aquatic Acute 1 Aquatic Chronic 1 Carc. 1A Repr. 1B	≥ 25 % ≥ 20 % ≥ 10 % ≥ 22.5 % ≥ 10 % ≥ 1.0 % ≥ 1 % ≥ 25 % ≥ 0.25 % ≥ 0.1 % ≥ 0.3 %	°Y Y Y Y Y Y Y °Y Y Y Y	HP6 HP14 HP13 HP6 HP13 HP11 HP5 HP14 HP14 HP7 H10
	NiO(OH)	15–25 %	12026-04-9	Notified C&L	H302 H317 H332 H351 H400 H410	Acute Tox. 4 Skin Sens. 1 Acute Tox. 4 Carc. 2 Aquatic Acute 1 Aquatic Chronic 1	≥ 25 % ≥ 10 % ≥ 22.5 % ≥ 1 % ≥ 25 % ≥ 0.25 %	°Y Y Y Y N Y	HP6 HP13 HP6 HP7 HP14 HP14
Anode	AB5	25–45 %	not found	-	-	-	-	-	-
	Rare earth oxide[51]	5–15 %	68188-83-0	Notified C&L	H319 H400 H410	Eye Irrit. 2 Aquatic Acute 1 Aquatic Chronic 1	≥ 20 % ≥ 25 %	N N Y	HP4 HP14 HP14

[51] Rare earth oxides comprising of cerium dioxide and lanthanum oxide

							≥ 0.25 %		
	Ni metallic (massive)	≤10 %	7440-02-0	Multiple harmonised classifications	H317 H351 H372	Skin Sens. 1 Carc. 2 STOT RE 1	≥ 10 % ≥ 1.0 % ≥ 1 %	N Y Y	HP13 HP17 HP5
	Ni metallic (powder; particle diameter < 1 mm)	≤10 %	7440-02-0	Multiple harmonised classifications	H317 H351 H372 H412	Skin Sens. 1 Carc. 2 STOT RE 1 Aquatic Chronic 3	≥ 10 % ≥ 1.0 % ≥ 1 % ≥ 25 %	N Y Y N	HP13 HP17 HP5 HP14
	Cobalt hydroxide	≤7 %	21041-93-0	REACH registration C&L	H302 H317 H319 H332 H334 H400 H410	Acute Tox. 4 Skin Sens. 1 Eye Irrit. 2 Acute Tox. 1 Resp. Sens. 1B Carc. 1B Repr. 1B Aquatic Acute 1 Aquatic Chronic 2	≥ 25 % ≥ 10 % ≥ 20 % ≥ 22.5 % ≥ 10 % ≥ 25 % ≥ 0.25 %	N N N N N N Y	HP6 HP3 HP4 HP6 HP13 HP14 HP14
	Cr	≤3 %	7440-47-3	REACH registration C&L	-	not classified	-	-	-
	Mn	≤2 %	7439-96-5	REACH registration C&L	-	not classified	-	-	-
Electrolyte	KOH	5–15 %	1310-58-3	Harmonised C&L	H302 H314	Acute Tox. 4 Skin Corr. 1A	≥ 25 % ≥ 5 %	N Y	HP6 HP8
	NaOH	5–15 %	1310-73-2	Harmonised C&L	H314	Skin Corr. 1A	≥ 5 %	Y	HP8

Reactions during NiMH battery life time and end-of-life processing

At the moment of disposal the state-of-charge of a NiMH battery is generally unknown (although future evolutions may allow processors to directly or indirectly access the battery state of charge). Depending on the state of charge, the waste NiMH contains $Ni(OH_2)$ or ($NiO(OH)$). The overall reaction taking place in a NiMH is (Zhang and Revathi, 2016):

$$Ni(OH)_2 + M \rightleftharpoons NiO(OH) + MH$$

Waste Sodium-Nickel-Chloride battery (ZEBRA)

This molten salt battery is based primarily on nickel metal and nickel salts as well as of the abundant sodium and chloride ions. A ZEBRA[52] battery contains the two electrolytes $NaAlCl_4$ and the so called BASE, a ceramic electrolyte. The $NaAlCl_4$ is formed by sodium chloride (NaCl) and aluminium chloride ($AlCl_3$) at the operational temperature of the battery. This electrolyte is also called molten salt electrolyte. According to (Trickett, 1998) ZEBRA batteries can also contain small amounts (< 1 %) of sodium fluoride (NaF) and iron sulphide (FeS). The chemical compositions as well their weight-% share on the total battery mass of the $Na\text{-}NiCl_2$ battery types is given in the following **Table 16** (Nikolic et al., 2023). According to the comments from the stakeholder consultation, ZEBRA batteries do not contain any organic material, therefore no POPs are expected to be present (FZSONICK, 2023).

Table 16. Battery components of $Na\text{-}NiCl_2$ batteries, their chemical compounds and the % share on the total battery mass (FZSONICK, 2023)

Battery component	$Na\text{-}NiCl_2$ (ZEBRA battery)	
	Compound	Weight (% total battery)
Cathode	$NiCl_2$ NaCl Ni (metallic) $FeCl_2$ Na Al	0–5.5% 0–9.3% 9–12% 0–3.6%, 0–0.1% 0–0.12%
Cathode current collector	Ni	4.8%
Cathode plate	Aluminium	no data
Anode	Liquid sodium (Na)	0–3.8%
Anode current collector	Fe	8.1%
Electrolyte	$NaAlCl_4$	11.2%
Separator	β”–Al_2O_3 (beta-alumina solid electrolyte (($Na_{1.7}Li_{0.3}Al_{10.7}O_{17}$)); BASE = ceramic electrolyte) (separator and solid electrolyte) Polyolefin	14.5%
Other	Fe NaF FeS	0–1.6% 0–0.35% 0–0.38%
Case and tab	Steel, plastic	34%

Chemical compounds of $Na\text{-}NiCl_2$ waste batteries and their hazardous properties

[52] ZEBRA: Zeolite Battery Research Africa Project

The following **Table 17** presents examples of the chemical compounds used in Na-$NiCl_2$ batteries, along with CAS number and hazard statement/hazard class and category code.

Table 17. Chemical compounds in Na-$NiCl_2$ batteries with hazard identification according to CLP (1272/2008)

Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
$NiCl_2$	0–5.5%	231-743-0	Harmonised C&L	H301	Acute Tox. 3	≥ 5.0 %	°Y	HP6
				H315	Skin Irrit. 2	≥ 20 %	N	HP4
				H317	Skin Sens. 1	≥ 10 %	N	HP13
				H331	Acute Tox. 3	≥ 3.5 %	°Y	HP6
				H334	Resp. Sens. 1	≥ 10 %	N	HP13
				H341	Muta. 2	≥ 1.0 %	Y	HP11
				H350i	Carc. 1A	≥ 0.1 %	Y	HP7
				H360D	Repr. 1B	≥ 0.3 %	Y	HP10
				H372	STOT RE 1	≥ 1.0 %	Y	HP5
				H400	Aquatic Acute 1	≥ 25 %	N	HP14
				H410	Aquatic Chronic 1	≥ 0.25 %	Y	HP14
NaCl	0–9.3%	7647-14-5	REACH registration C&L	-	not classified	-	-	-
Ni metallic (powder; particle diameter < 1 mm)	9–12%	7440-02-0	Multiple harmonised classifications	H317	Skin Sens. 1	≥ 10 %	°Y	HP13
				H351	Carc. 2	≥ 1.0 %	Y	HP7

				H372 H412	STOT RE 1 Aquatic Chronic 3	≥ 1.0 % ≥ 25 %	Y N	HP5 HP14
$FeCl_2$	0–3.6%,	7705-08-0	REACH registration C&L	H290 H302 H315 H318	Met. Corr. 1 Acute Tox. 4 Skin Irrit. 2 Eye Dam. 1	No value ≥ 25 % ≥ 20 % ≥ 10 %	N N N N	- HP6 HP4 HP4
Na	0–3.8%	7440-23-5	Harmonised C&L	H260 H314	Water-react. 1 Skin Corr. 1B	≥ 0.2 % ≥ 5 %	°Y N	HP3 HP8
$NaAlCl_4$	11.2%	7784-16-9	Notified C&L	H314 H318	Skin Corr. 1B Eye Dam. 1	≥ 5 % ≥ 10 %	Y Y	HP8 HP4
β”-Al_2O_3	14.5%	not found	-	-	-	-	-	-
NaF	0–0.35%	7681-49-4	Harmonised C&L	H301 H315 H319	Acute Tox. 3 Skin Irrit. 2 Eye Irrit. 2	≥ 5 % ≥ 20 % ≥ 20 %	N N N	HP6 HP4 HP4
FeS	0–0.38%	1317-37-9	REACH registration C&L	-	not classified	-	-	-

For certain substances used in Na-$NiCl_2$ batteries, no entries were found in the C&L inventory for β”-Al_2O_3 (beta-alumina solid electrolyte).

Reactions during battery life time and end-of-life processing

The ZEBRA system is based on the following principle cell reaction (Böhm and Beyermann, 1999):

Equation 4 $Ni + 2\ NaCl \rightleftharpoons NiCl_2 + 2Na$

In addition, during the battery lifetime, the metals Al and Fe also react with the sodium chloride to form $NaAlCl_4$ and $FeCl_2$ (FZSONICK, 2023)

Equation 5 $Al + 4\ NaCl \rightleftharpoons NaAlCl_4 + 3Na$

Equation 6 $Fe + 2\ NaCl \rightleftharpoons FeCl_2 + 2\ Na$

The reaction products described in the equation above are considered in Table 17.

Chemical reactions in case the integrity of the batteries is compromised:

In case the integrity of batteries is compromised, the sodium tetrachloroaluminate reacts with sodium to produce aluminium and sodium chloride:

Equation 7 $NaAlCl_4 + 3\ Na \rightleftharpoons Al + 4\ NaCl$

Recommendation on classification of nickel-based waste batteries and recommendation for new waste codes

NiMH:

Cathode material: The cathode material of NiMH consists of two nickel compounds ($Ni(OH)_2$ and/or $NiO(OH)$) which account for 15–25 % of the battery mass. Both chemical compounds have hazardous statement codes that exceed the related concentration limit values significantly (e.g. mutagenic, carcinogenic, reproduction) (EC, 2018). Exceeding mutagenic (HP11), carcinogenic (HP7) and reproduction (HP10), the waste needs to be **classified as hazardous if the concentration limits are equalled or exceeded,** as concentration limits have been assigned for the hazardous properties HP4–HP8, HP10, HP11, HP13, and HP14.

Electrolyte: The electrolyte consists either of KOH or NaOH in concentration of 5–15 %. Both compounds have hazardous statement codes that exceed the related concentration limit values for H314 (Skin Corr. 1A).

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition (including the variability) as well as the classification of the chemical compounds contained, the JRC proposes to classify **NiMH waste batteries as absolute hazardous.**

Na-$NiCl_2$:

Na-$NiCl_2$ waste batteries contain several chemical compounds in such concentration, that the limit values for hazardous classification are exceeded.

Cathode material: $NiCl_2$ is used in Na-$NiCl_2$ batteries and several hazard statement codes are assigned with low limit values (Muta. 2: ≥ 1.0 %; Carc. 1A: ≥ 0.1 %; Repr. 1B: ≥ 0.3 %). The Na-$NiCl_2$ content is 0–5.5 %. Therefore, it is highly likely, that the limit values are exceeded.

Example 2: Ni is present in a metallic and powdery form in the cathode material in concentration of 9–12 %. The hazardous statement code H351 (limit value ≥ 1.0 %) and H 372 (limit value: ≥ 1 %) trigger hazardous classification for the hazardous properties HP7 and HP5, respectively.

Electrolyte: The $NaAlCl_4$ that is part of a new battery but is also formed during the charging and discharge process can be found in concentration of around 11 %. This chemical compound has two properties (Skin Corr. 1B and Eye Dam. 1) and the concentration in the waste battery is higher than the defined limit values, therefore triggering the hazardous properties HP8 and HP4.

Based on the information known to date on the qualitative and quantitative composition (including the variability) as well as the classification of the chemical compounds contained, the JRC proposes to **classify Na-NiCl$_2$ as absolute hazardous.**

Recommendation for new waste codes for nickel-based batteries in the LoW

Based on the information known to date on the qualitative and quantitative composition (including the variability), the classification of the chemical compounds contained and the formation of new compounds with hazardous properties during life time, the JRC proposes to **classify all nickel-based waste batteries as absolute hazardous**.

Based on the approach to the extension of the LoW in Spain (see **Table 4**), the JRC proposes to introduce new absolute hazardous waste codes for all nickel-based waste batteries under scope in the sub-chapter “16 06” and “20 01 Separate collected fraction (except 15 01)”, the sub-chapter of chapter 20, municipal waste:

- 16 06 09* Waste nickel-based batteries other than those mentioned in 16 06 02 (e.g. NiMH, Na-NiCl$_2$)
- 20 01 33* Waste batteries included in categories 16 06 01 to 16 06 04, 16 06 07 to 16 06 11, 16 06 13 and unsorted waste batteries containing those waste batteries

4.2.4. Waste alkaline-based batteries

Alkaline-based batteries derive energy from the reaction between a zinc metal (anode) and manganese dioxide (cathode; MnO_2). Compared with zinc–carbon or zinc chloride batteries, that use acidic ammonium chloride (NH_4Cl) or zinc chloride ($ZnCl_2$) as electrolyte, the most commonly used electrolyte for an alkaline battery is potassium hydroxide (KOH). This alkaline electrolyte is also the namesake of the alkaline battery. Other components are graphite (carbon rod as collector), separator and binder, gasket and the casing (mainly nickel plated steel; see **Table 18**, source: Safety Data Sheets from battery producers).

Table 18. Battery components of waste alkaline-based batteries, their chemical compounds and the % share on the total battery mass

Battery component	Chemical compound	Weight (% total battery)
Cathode	MnO_2, $BaSO_4$, Ag-catalyst	25–50 %
Cathode current collector	Carbon	2–6 %
Anode	Zn (metallic) in gel	10–25 %
Anode current collector	Brass	0.2–2%
Electrolyte	KOH	4–15 %
Separator	Cellulose & Polyacrylic Acid	0–1 %
Binder	Polyacrylic Acid (PAA)	0–1 %
Gasket	Nylon	0–2 %
Other isolators	Polyolefin	0–2 %
Case and tab	Nickel plated steel	15–30 %

Reactions during battery life time and end-of-life processing

The overall reactions in the alkaline battery is as follows (Energizer Brands, 2018):

Equation 8 $Zn + 2\ MnO_2 + 2\ H_2O \rightleftharpoons Zn(OH)_2 + 2\ MnO(OH)$

Equation 9 $2\ Zn + 3\ MnO_2 \rightleftharpoons 2\ ZnO + Mn_3O_4$

A comparison with the CL inventory reveals, that di-manganese tri-oxide (Mn_2O_3; CAS No. 1317-34-6, REACH registration C&L) is not classified. However, for zinc oxide (ZnO; CAS No. 1314-13-2) two hazard statement codes are assigned (H400 (Aquatic Acute 1); H410 (Aquatic Chronic 1)).

Equation 10 $2\ Zn + O_2\ (air) \rightleftharpoons 2\ ZnO$

Equation 11 $2\ KOH + CO_2\ (air) \rightleftharpoons K_2CO_3 + H_2O$

Composition of alkaline-based waste batteries and their hazardous properties

The following **Table 19** presents examples of chemical compounds used in alkaline-based batteries, the chemical compounds that can be formed, along with CAS number and hazard statement/hazard class and category code.

Table 19. Overview on battery components, their chemical compound and % weight of waste alkaline-based batteries with hazard identification according to CLP (1272/2008)

Battery component	Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Cathode	MnO_2	25–50 %	1313-13-9	Harmonised C&L	H302 H332	Acute Tox. 4 Acute Tox. 4	≥ 25 % ≥ 22.5 %	Y Y	HP6 HP6
	Mn_2O_3	unknown	1317-34-6	REACH registration C&L	-	not classified	-	-	-
	$BaSO_4$	unknown	7727-43-7	REACH registration C&L	-	not classified	-	-	-
Anode	Zn metallic (Zinc powder – zinc dust)	10–25 %	7440-66-6	Multiple harmonised classifications	H260 H400 H410	Water-react. 1 Aquatic Acute 1 Aquatic Chronic 1	0.3 % ≥ 25 % ≥ 0.25 %	Y °N Y	HP3 HP14 HP14
	ZnO	unknown	1314-13-2	Harmonised C&L	H400 H410	Aquatic Acute 1 Aquatic Chronic 1	≥ 25 % ≥ 0.25 %	- -	HP14 HP14
Carbon	Graphite	2–6 %	7782-42-5	REACH registration C&L	-	not classified	-	-	-

Electrolyte	KOH	5–15 %	1310-58-3	Harmonised C&L	H302 H314	Acute Tox. 4 Skin Corr. 1A	≥ 25 % ≥ 5 %	N Y	HP6 HP8
Binder	PAA[53]	0–1 %	9003-01-4	REACH registration C&L	H302 H318 H335 H412	Acute Tox. 4 Eye Dam. 1 STOT SE 3 Aquatic Chronic 3	≥ 25 % ≥ 10 % ≥ 20 % ≥ 25 %	N N N N	HP6 HP4 HP5 H14
	PAA[54]	0–1 %	9003-01-4	Notified C&L	-	not classified	-	-	-
Reaction compound	K_2CO_3	unknown	584-08-7	REACH registration C&L	H315 H319 H335	Skin Irrit. 2 Eye Irrit. 2 STOT SE 3	≥ 20 % ≥ 20 % ≥ 20 %	- - -	HP4 HP4 HP5

[53] 2-Propenoic acid, homopolymer
[54] 2-Propenoic Acid, Polymer

Recommendation on classification of alkaline waste batteries and recommendation for new waste codes

Waste alkaline-based batteries contain several chemical compounds that results in a classification as hazardous waste.

Cathode material: The cathode material of alkaline-based batteries (MnO_2) is classified with two hazard statement codes.

1) H302 (Acute Tox. 4 (oral.)) - harmful if swallowed. The concentration limit of the individual substance **to be classified as hazardous HP 6 (Acute toxicity) is ≥ 25 %** (EC, 2018). In alkaline-based batteries, the cathode material accounts for 25-50 % of the battery mass, therefore it is highly likely, that the limit values are exceeded.
2) H332 (Acute Tox. 4 (Inhal.)) - harmful if inhaled. The concentration limit of the individual substance **to be classified as hazardous HP 6 (Acute toxicity) is ≥ 22.5 %** (EC, 2018). In alkaline-based batteries, the cathode material accounts for 25–50 % of the battery mass, therefore it is highly likely, that the limit values are exceeded.

Anode material: The anode contains zinc powder in its metallic form. Zinc powder has the hazardous statement code H260 (Water-react. 1). The concentration limit of the individual substance to be classified as hazardous HP 3 (flammable) is ≥ 0.3 % (EC, 2018). In alkaline-based batteries, the cathode material accounts for 10–25 % of the battery mass. Furthermore, the hazardous statement code H410 (Aquatic Chronic 1) is assigned. The concentration limit of the individual substance to be classified as hazardous HP 14 (Ecotoxic) is ≥ 0.25 % (EC, 2018). In alkaline-based batteries, the cathode material accounts for 10–25 % of the battery mass.

As described in section 2.2.3, Step 3 of the hazard determination, concentration limits have been assigned for the hazardous properties HP4–HP8, HP10, HP11, HP13, and HP14. A waste should be classified as hazardous if the concentration limits are equalled or exceeded. As the alkaline-based batteries exceed the limit value considerably, these alkaline waste batteries are classified as absolute hazardous.

Electrolyte: Potassium hydroxide (KOH) is the electrolyte and is classified with the hazard statement code H314 (Skin corr. 1A, 1B, or 1C) that causes severe skin burns and eye damage. When a waste contains one or more substances classified as Skin corr.1A, 1B or 1C (H314) and the sum of their concentrations exceeds or equals 5 %, the waste should be classified as hazardous by HP 8 (EC, 2018). In alkaline-based batteries, the content of KOH is 5–15 %.

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition (including the variability), the classification of the chemical compounds contained and the formation of new compounds with hazardous properties during life time, the JRC proposes to **classify alkaline-based waste batteries as absolute hazardous,** even though these batteries are currently assigned to the non-hazardous waste code 16 06 04.

Recommendation for new waste codes for alkaline-based batteries in the LoW

The JRC proposes to amendment the LoW for waste alkaline-based batteries and to **change the existing absolute non-hazardous waste code 16 06 04 to an absolute hazardous 16 06 04*** “waste alkaline-based batteries (except 16 06 03)”.

4.2.5. Waste zinc-based batteries

Basically, zinc-based batteries use zinc ions (Zn^{2+}) as the charge carriers (anode). Zinc-based batteries can be subdivided into zinc-carbon, zinc-chloride and zinc-air batteries. In addition, silver zinc-based batteries also use Zn in their anode. Therefore, these batteries are also considered in this section. Depending on the zinc battery type, different anodes and electrolytes are part of the battery cell. **Table 20** describes the battery components and chemical compounds of zinc-based batteries.

Table 20. Battery components and compounds of zinc-based batteries

Battery component	Zinc-carbon	Zinc-chloride	Zinc-air	Silver zinc	Silver oxide
	Zn-C	Zn-Cl	-	Ag-Zn	Ag-oxide
Cathode	MnO_2	MnO_2	O_2	$Ag_{(met)}$	Ag_2O (Ag(I)O)
Cathode catalyst	-	-	Carbon; Mixed Mn-oxides; Polytetrafluoroethylene (PTFE)	-	-
Cathode current collector	-	-	Nickel (wire mesh)	-	-
Anode	Zn	Zn	Zn	Zn and ZnO	Zn
Anode current collector	-	-	Copper plating	-	-
Electrolyte	Mainly 20 % NH_4Cl, ZnCl (only part of the electrolyte)	only ZnCl	KOH	KOH	NaOH, KOH
Collector	Carbon rod	Carbon rod	-	-	-
Separator	-	-	Polyolefin	membrane	membrane
Casing	Zn anode is at the same time battery can, steel on bottom and cap		Steel	Zn anode is at the same time battery can, Ag cathode is also part of the can.	-
Other	Carbon rod, cardboard		Lead	Plastic insulator (sealant), MnO_2, graphite, can contain low concentration of mercury oxide	

Table 21 shows the weight of the different components related to the total battery (%). The JRC literature research, mainly based on Safety Data Sheets from battery producers, revealed a great variability of certain components, even within the same battery chemistry. In the SDSs for the silver

containing batteries, the percentwise weight distribution of the battery components was somehow similar for silver zinc and silver oxide batteries, so no clear distinction between the two battery chemistries is presented in the table below.

Table 21. Percentwise weight distribution of the zinc-based battery components (sources are Safety Data Sheets from battery producer)

Battery component	Zinc-carbon	Zinc-chloride	Zinc-air	Silver zinc	Silver oxide
	Weight (% total battery)				
Zn metallic	20–25 %	50–70 %	50–70 %	2–15 %	
MnO_2	40–50 %	10–20 %	-	0–3 %	
AgO	-	-	-	5–40 %	
NH_4Cl and ZnCl	10–20 %	15–30 %	-	-	
KOH	–	–	< 10 %	0–10 %	
Carbon (rod)	5–6 %	5–15 %	-	0–5 %	
HgO	-	-	-	0–max. 1 %	
Other components (includes water, separator, binders, conductive agents)	10–15 %	–	< 10 %	unknown	
Steel	-	-	-	30–40 %	

Composition of zinc waste batteries and their hazardous properties

The following **Table 22** presents examples of chemical compounds used in zinc-based batteries, along with CAS number and hazard statement/hazard class and category code.

Table 22. Overview on different zinc-based batteries with hazard identification according to CLP (1272/2008)

Chemical compound		CAS No.	Source	Hazard statement code, hazard class and category code	
Zinc carbon and zinc chloride					
MnO_2	Manganese dioxide	1313-13-9	Harmonised C&L	H302 H332	Acute Tox. 4 Acute Tox. 4
Zn metallic	Zinc powder – zinc dust	7440-66-6	Multiple harmonised classifications	H250 H260 H400 H410	Pyr. Sol. 1 Water-react. 1 Aquatic Acute 1 Aquatic Chronic 1
NH_4Cl	Ammonium chloride	12125-02-9	Harmonised C&L	H302 H319	Acute Tox. 4 Eye Irrit. 2
ZnCl	Zinc chloride	7646-85-7	Harmonised C&L	H302 H314	Acute Tox. 4 Skin Corr. 1B

				H400 H410	Aquatic Acute 1 Aquatic Chronic 1
Zinc air					
Zn metallic	Zinc powder – zinc dust	7440-66-6	Multiple harmonised classifications	H250 H260 H400 H410	Pyr. Sol. 1 Water-react. 1 Aquatic Acute 1 Aquatic Chronic 1
KOH	Potassium hydroxide	1310-58-3	Harmonised C&L	H302 H314	Acute Tox. 4 Skin Corr. 1A
Silver zinc					
Zn metallic	Zinc powder – zinc dust	7440-66-6	Multiple harmonised classifications	H250 H260 H400 H410	Pyr. Sol. 1 Water-react. 1 Aquatic Acute 1 Aquatic Chronic 1
ZnO	Zinc oxide	1314-13-2	Harmonised C&L	H400 H410	Aquatic Acute 1 Aquatic Chronic 1
NaOH	Sodium hydroxide	1310-73-2	Harmonised C&L	H314	Skin Corr. 1A
HgO	Mercuric oxide / Mercury(II) oxide	21908-53-2	Notified C&L	H300 H310 H330 H373 H400 H410	Acute Tox. 2 Acute Tox. 1 Acute Tox. 2 STOT RE 2 Aquatic Acute 1 Aquatic Chronic 1
Silver oxide					
Zn metallic	Zinc powder – zinc dust	7440-66-6	Multiple harmonised classifications	H250 H260 H400 H410	Pyr. Sol. 1 Water-react. 1 Aquatic Acute 1 Aquatic Chronic 1
Ag_2O	Di-silver oxide (Ag(I)O)	20667-12-3	REACH registration C&L	H271 H318 H360D H400 H410	Ox. Sol. 1 Eye Dam. 1 Repr. 1B Aquatic Acute 1 Aquatic Chronic 1
KOH	Potassium hydroxide	1310-58-3	Harmonised C&L	H302 H314	Acute Tox. 4 Skin Corr. 1A
NaOH	Sodium hydroxide	1310-73-2	Harmonised C&L	H314	Skin Corr. 1A
HgO	see silver zinc battery				

Zinc-air batteries

Table 23. Chemical compounds in Zn-air batteries with hazard identification according to CLP (1272/2008)

Battery component	Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Cathode	Carbon	1–3 %	7440-44-0	Notified C&L	H319 H335	Eye Irrit. 2 STOT SE 3	≥ 20 % ≥ 20 %	N N	HP4 HP5
	Mixed Mn-oxides (e.g. MnO_2)	0–2 %	1313-13-9	Harmonised C&L	H302 H332	Acute Tox. 4 Acute Tox. 4	≥ 25 % ≥ 22.5 %	N N	HP6 HP6
	PTFE	0–2 %	9002-84-0	Notified C&L	-	not classified	-	-	-
Cathode collector	Nickel (wire mesh)	3–7 %	7440-02-0	Multiple harmonised classifications	H317 H351 H372	Skin Sens. 1 Carc. 2 STOT RE 1	≥ 10 % ≥ 1.0 % ≥ 1 %	N Y Y	HP13 HP7 HP5
Anode	Zinc metallic (Zinc powder – zinc dust)	30–40 %	7440-66-6	Multiple harmonised classifications	H260 H400 H410	Aquatic Acute 1 Aquatic Chronic 1	0.3 % ≥ 25 % ≥ 0.25 %	Y Y Y	HP3 HP14 HP14
Anode collector	Copper [55] (plating)	2–6 %	7440-50-8[56]	Harmonised C&L	-	-	-	-	-
Electrolyte	KOH	1–3 %	1310-58-3	Harmonised C&L	H302 H314	Acute Tox. 4 Skin Corr. 1A	≥ 25 % ≥ 5 %	N N	HP6 HP8
Casing	Steel	30–40 %	12597-69-2	Notified C&L	-	not classified	-	-	-
Other	Lead	0.015–0.020 %	7439-92-1[57]	Multiple harmonised classifications	H360FD H362 H400 H410	Repr. 1A Lact. Aquatic Acute 1 Aquatic Chronic 1	≥ 0.3 % Not available ≥ 25 % ≥ 0.25 %	N N N N	HP10 - HP14 HP14

Reactions during battery life time and end-of-life processing

Electrochemical processes during the use of zinc-based batteries might also cause the new formation of chemicals compounds with hazardous properties. The following list gives examples of the overall reaction within the different type of batteries:

Zinc-carbon:

Equation 12 $Zn + 2MnO_2 + 2NH_4Cl \rightleftharpoons 2MnO(OH) + [Zn(NH_3)_2]Cl_2$

Zinc-chloride:

[55] not classified due to presence in massive form
[56] Granulated copper; [particle length: from 0,9 mm to 6,0 mm; particle width: from 0,494 to 0,949 mm]
[57] lead powder; [particle diameter < 1 mm]

$$\textbf{Equation 13} \quad Zn + 2MnO_2 + H_2O \rightleftharpoons Mn_2O_3 + Zn(OH)_2$$

Zinc-air:

$$\textbf{Equation 14} \quad Zn + O2\ (air) \rightleftharpoons 2\ ZnO$$

Silver-zinc:

During the charging process, silver is first oxidized to silver(I) oxide

$$\textbf{Equation 15} \quad 2Ag(s) + 2OH^- \rightarrow Ag_2O + H_2O + 2\ e^-$$

Then to silver(II) oxide

$$\textbf{Equation 16} \quad Ag_2O + 2OH^- \rightarrow 2AgO + H_2O + 2\ e^-$$

Zinc oxide is reduced to metallic zinc:

$$\textbf{Equation 17} \quad Zn(OH)_2 + 4\ e^- \rightleftharpoons 2\ Zn + 4\ OH^-$$

Silver-oxide:

Overall reaction:

$$\textbf{Equation 18} \quad Zn + H_2O + Ag_2O \rightleftharpoons Zn(OH)_2 + 2Ag$$

Overall reaction (anhydrous form):

$$\textbf{Equation 19} \quad Zn + Ag_2O \rightleftharpoons ZnO + 2Ag$$

Chemical reactions in case the integrity of the batteries is compromised

$$\textbf{Equation 20} \quad 2\ KOH + CO_2\ (air) \rightarrow K_2CO_3 + H_2O$$

A detailed table containing the chemical compounds that are formed during the electrochemical processes in Zn-based batteries with hazard identification is presented in Annex 9 (**Table 47**).

Recommendation on classification of zinc-based waste batteries and recommendation for new waste codes

All zinc based batteries under scope contain zinc in its metallic form and/or different zinc compounds (e.g. Zn metallic, ZnCl, ZnO, Ag_2O) with the **hazard statement code H410 (Aquatic chronic)** that is very toxic to aquatic life with long lasting effects**.** The concentration limit of the individual substance or sum of substances to be classified as hazardous HP 14 (Ecotoxic) is ≥ 0.25 % (EC, 2018). As zinc based chemical compounds are the main constituent of these batteries, the limit value of ≥ 0.25 % will be exceeded.

In addition, in all cases other chemical compounds present in the different types of batteries (under various assumptions on the state of charge and relative changes in concentrations) present hazard characteristics, which will overall trigger a hazard classification with a very high degree of certainty.

Recommended hazard classification:

Based on the information available to the JRC on the qualitative and quantitative composition (including the variability), the classification of the chemical compounds contained and the formation of new compounds with hazardous properties during their life time, the JRC proposes to **classify zinc-based waste batteries as absolute hazardous,** even though these batteries are currently captured under the non-hazardous waste code 16 06 05.

Recommendation for new waste codes for zinc-based batteries in the LoW:

The JRC proposes to amend the LoW entry currently applied to waste zinc-based batteries (the existing absolute non-hazardous waste code 16 06 05) and to assign to this waste a newly created hazardous mirror entry with code 16 06 10* “Waste zinc-based batteries, including silver oxide batteries” .

NB For clarity and alignment to terminology in the Battery Regulation, it is also proposed to amend the definition of existing code 16 06 05 “Other batteries and accumulators” to “Waste batteries not otherwise specified other than those mentioned in 16 06 07”, with the creation of a mirror code 16 06 07* “Waste batteries not otherwise specified containing hazardous substances”.

4.2.6. Waste sodium-based batteries

Waste sodium-ion batteries (SIB)

The three main Na-ion cathode variants that are used in SIB are “prussian white” (Sodium iron(II)-hexacyanoferrate(II); $Na_2Fe[(Fe(CN)_6])$, layered oxide ($NaMO_2$) or polyanion (e.g. $Na_3V_2(PO_4)_2F_3$) (Yang et al., 2019). Prussian white is considered one of the most promising cathode materials for sodium-ion batteries due to its physical and chemical characteristics (e.g. large ion diffusion channels, low lattice strain), ease of preparation, low costs but also because of its alleged low toxicity (Sun and You, 2012). Hard carbon is used as anode material. The collectors for cathode and anode are made of aluminium. The electrolyte consists of organic carbonates such as propylene carbonates, sodium salts and/or hexafluorophosphate.

The electrolytes of SIBs and LIBs use similar carbonate solvents such as e.g. ethylene carbonate (EC) and dimethyl carbonate (DMC). The difference to lithium-based batteries is, that SIB commonly use sodium hexafluorophosphate ($NaPF_6$), as opposed to lithium hexafluorophosphate ($LiPF_6$) in lithium-based batteries. A single sodium ion battery (SIB) cell consists of the components and compounds presented in **Table 24** (EASE, 2016; Kitajou et al., 2022; Tang et al., 2016; Woodmac, 2023; Zhao et al., 2023).

Table 24. Battery components and compounds of sodium-based batteries

Battery component	Na-ion batteries	
	Compound	Weight (% total battery)
Cathode material	Prussian white: could be $Na_2Fe[(Fe(CN)_6]$ Layered oxide: e.g. $NaTi_2(PO_4)_3$ Polyanion: e.g. $NaFePO_4$ or Na_2FePO_4 $Na_3V_2(PO_4)F_3$	35–40 %
Cathode current collector	Aluminium	8–10 %
Anode material	Hard carbons or intercalation compounds	25–35 %
Anode current collector	Aluminium	8–10 %
Electrolyte	Examples: – Aqueous solution: Na_2SO_4 – Non-aqueous: salts in PC (propylene carbonate) – $NaPF_6$ – EC, DMC, PC	10–15%
Binder	Polyvinylidene fluoride (PVDF)	3 %
Conductivity agent	Nanocarbon materials	2–3 %
Separator	Polyolefin membranes Polyolefin membranes coated with ceramic particles.	2–3 %
Case and tab	Steel, plastic	5 %

Chemical compounds of sodium waste batteries and their hazardous properties

For some of the chemical constituents no CAS No. is assigned or the CAS No. could not be found. For those for which an entry exists in the C&L database, no hazardous statement code is assigned, with the exception of propylene carbonate with the hazardous statement code H319 (Eye Irrit. 2) (Table 30). SIB typically contain the same electrolyte as lithium-based batteries. As shown in Annex 6 – Table 44, most of the organic solvent electrolytes have hazardous properties.

Table 25. Overview on different sodium waste batteries compounds with hazard identification according to CLP (1272/2008)

Chemical compound		Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
$Na_3V_2(PO_4)F_3$	Sodium Vanadium Phosphate	-	not found	-	-	-		-	
$NaFePO_4$	Sodium Iron Phosphate	-	unassigned	-	-	-		-	
Na_2FePO_4	Di-Sodium Iron Phosphate	-	7558-79-4	REACH registration C&L	-	not classified		-	
$NaTi_2(PO_4)_3$	Sodium Titanium Phosphate	-	unassigned	-	-	-		-	
Na_2SO_4	Sodium sulphate	-	7757-82-6	REACH registration C&L	-	not classified		-	
$C_4H_6O_3$	Propylene carbonate	-	108-32-7	Harmonised C&L	H319	Eye Irrit. 2	≥ 20 %	-	HP4
PF_6	Hexafluorophosphate	-	16919-18-9	No entries for this CAS number	-	-		-	
$NaPF_6$	Sodium hexafluorophosphate	-	21324-39-0	Notified C&L	H302 H312 H314 H332	Acute Tox. 4 Acute Tox. 4 Skin Corr. 1B Acute Tox. 4	≥ 25 % ≥ 55 % ≥ 5 % ≥ 22.5 %	- - - -	HP6 HP6 HP8 HP6

Waste Sodium-Sulphur batteries

Sodium–sulphur (NaS) batteries use sodium (Na, molten sodium metals) and sulphur (S) as the active materials for the cathodes and anodes. Beta-alumina (β-Al_2O_3) ceramics are used as both as the electrolyte and the separator (see **Table 26**). In order to reduce the transmission resistance of sodium ions in the alumina solid electrolyte, it is necessary to ensure that the electrode material is in a molten state. The working temperature is set at 250–300 °C (Wang et al., 2022, 2021). However, further developments were made to perform at room temperature reducing the risk of explosion, energy consumption and corrosion of high temperature sodium-sulphur batteries (Wang et al., 2021).

Table 26. Battery components of Na-S batteries, their chemical compounds and the % share on the total battery mass

Battery component	Sodium-sulphur	
	Compound	Weight (% total battery)
Cathode	Liquid sulphur	40–50 %
Anode	Molten sodium metal Na_2S_x (Sodium polysulphide) e.g. Na_2S_3, Na_2S_2, Na_2S	10–20 %
Electrolyte Separator	Na-beta-alumina (Al_2O_3) (Beta-alumina solid electrolyte – BASE)	5–15 %
Case and tab	Steel, plastic	15–20 %

Chemical compounds of sodium-sulphur waste batteries and their hazardous properties

Table 27. Chemical compounds of sodium-sulphur batteries with hazard identification according to CLP (1272/2008)

Battery component	Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Cathode	S	40–50 %	7704-34-9	Harmonised C&L	H228 H315	Flamm. solid Skin Irrit. 2	- ≥ 20 %	Y Y	HP 6 HP 4
Anode	Na	10–20 %	7440-23-5	Harmonised C&L	H260 H314	Water-react. 1 Skin Corr. 1B	0.1 % ≥ 5 %	Y Y	HP 6 HP 8
Electrolyte and Separator	Beta-alumina solid electrolyte	5–15 %	11138-49-1	REACH registration C&L	H290 H314 H318	Met. Corr. 1 Skin Corr. 1A Eye Dam. 1	- ≥ 5 % ≥ 10 %	- °Y °Y	- HP 8

									HP 4
	Aluminium(III) oxide	1–2 %	1344-28-1	REACH registration C&L	-	not classified	-	-	-

Reactions during battery life time and end-of-life processing

Sodium is strongly reactive and presents a hazard because it spontaneously burns and can explode when exposed to water, steam, air or moist air. This requires that the anode is handled in a dry or inert atmosphere until the battery is sealed (Spoerke et al., 2021). The Commission notice on technical guidance on the classification of waste, lists sodium (Hazard Statement Codes: H260) in its Table 11 (Examples of substances which may cause a waste to exhibit HP 3 Flammable (fifth indent) and their threshold concentrations) with a concentration limit of sodium metal for waste to be H3-A is 0.2 %.

One example of the reactions taking place in a sodium-sulphur battery is given below:

Equation 21 $2\ Na + 4\ S \rightarrow Na_2S_4$ (sodium tetrasulphide)

During the charging and discharging, different sodium polysulphides (Na_2S_x) are formed (e.g. Na_2S, Na_2S_2, Na_2S_3). Annex 10 **(Table 48)** gives an insight into these chemical compounds as well as their related hazard identification.

Recommendation on classification of sodium-based waste batteries and recommendation for new waste codes

This section summarises the arguments for a proposal of a non-hazardous or hazardous classification for the sodium-based batteries under scope and proposes new waste codes for sodium-based waste batteries.

Sodium ion batteries

To date, sodium-ion batteries have hardly been used on a large scale. As these batteries are still under development, it is not yet possible to make a definitive final statement about their qualitative and quantitative composition. In fact, entries for some of the relevant substances used in the cathode or electrolyte of these batteries are missing in the CL inventory. Consequently, the JRC cannot propose a systematic hazardous classification for this type of sodium-based batteries. There, two new waste codes are proposed:

- 16 06 11* Waste sodium-based batteries containing hazardous substances (except 16 06 13)
- 16 06 12 Other waste sodium-based batteries

Sodium sulphur batteries

Cathode material:

The compounds of the cathode (sulphur) and the anode (sodium) are flammable or water reactive. Both substances have hazardous statement codes and associated limit concentration that are exceeded. Therefore, the JRC proposes a hazardous classification for these sodium-bases batteries.

Recommendation for new waste codes for sodium sulphur batteries batteries in the LoW:

Sodium-based batteries could play an important role in storing energy in the future for a variety of application (vehicles, grid stabilisation, and portable electronics). With this in mind, the JRC proposes to introduce a separate waste code for this type of waste sodium sulphur battery in anticipation:

- 16 06 13* Waste sodium sulphur batteries

4.2.7. Waste batteries not otherwise specified with hazardous properties

For non-hazardous waste battery chemistries that are not covered in the LoW, waste code 16 06 05 (waste batteries not otherwise specified other than those mentioned in 16 06 07) is applied. For hazardous waste battery chemistries that are not covered in the Low, the JRC proposes the following

Recommendation for new hazardous waste codes for batteries that not otherwise specified in the LoW:

For other battery chemistries with hazardous properties not otherwise specified in the LoW, the JRC proposes to assign these waste batteries to the new generic waste code in sub-chapter "16 06":

- 16 06 07* Waste batteries not otherwise specified containing hazardous substances

4.3. Intermediate fractions from battery waste treatment

4.3.1. Intermediate fractions from lead-acid waste battery recycling

As illustrated in section 2.1.4.1 and illustrated in **Figure 18**, lead battery recycling gives rise to several intermediates which consist of, or are contaminated with, lead metal and lead compounds (oxides, sulphates). NB. Most of these are treated in integrated recycling processes within the same facility; however, some may occasionally require designation under a waste code e.g. in case of transport.

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition and its variability, the classification of the chemical compounds contained the JRC proposes to **classify all intermediates from waste lead batteries and lead battery manufacturing waste as absolute hazardous.**

Recommendation for new waste codes for black masses from lithium-based batteries in the LoW:

The JRC proposes to introduce a new waste code for lead-acid battery waste intermediates in the chapter 19, sub-chapter "19 12 wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified":

- 19 12 13* Intermediate fraction from the thermal/mechanical treatment of waste lead-acid batteries and lead-acid battery manufacturing waste containing a mixture of electrode materials

4.3.2. Intermediate fractions from lithium-based waste battery recycling

As elaborated in section 2.1.4.1, various intermediate fractions are produced from the mechanical-, hydrometallurgical and pyrometallurgical recycling of lithium-based waste batteries. In the following sections the physical- and chemical properties, the weight distribution and the variability of substances and chemical compounds present in black mass (section 4.3.1.1), hydrometallurgical intermediates (section 4.3.1.2), alloys (section 4.3.1.3) and slag (section 4.3.1.4) are presented. Based on this information provided, the hazard determination was performed and a hazard classification is proposed.

4.3.2.1. Black mass from mechanical recycling of lithium-based waste batteries

The exact composition of black mass (BM) can vary significantly depending on the type of lithium battery entering a recycling process, its chemistry and the recycling process itself. As an example, with an upstream or downstream thermal treatment of the Li-based batteries or the black mass, electrolytes and plastics may be oxidised completely, resulting in them no longer being present in the black mass. Electrolytes can be specifically removed, for instance, by using vacuum drying.

According to data on LFP battery black masses that are available to us, the electrolytes contained in the black masses were removed by specific processes such as pyrolysis (BM 8 and 9) or vacuum drying (BM 10) (**Table 28**) .There is therefore no data available on black masses from LFP batteries, in which the electrolyte was not specifically removed. However, it can be assumed that without targeted removal, the electrolyte as well as the lithium salts are still contained in the black mass.

Also the black mass can have a certain water content if the crushing of the batteries is performed under water. **Table 28** provides detailed information for black masses recovered from lithium ion batteries and lithium iron phosphate batteries. Due to their very different composition, the lithium-based batteries containing metal oxides and lithium iron phosphate batteries are usually not recycled in the same recycling process as the other lithium battery chemistries. The table illustrates the composition of the black mass and its variability.

Table 28. Chemical compounds, their weight (percent) share in black mass recovered from lithium-based batteries with hazard identification according to CLP (1272/2008)

Black mass	BM1	BM2	BM3	BM4	BM5	BM6	BM7	BM8	BM9	BM10	Hazard statement code, hazard class and category code		Conc. limit
Input batteries	Unspecific, mix	LCO, NMC, NCA	NMC	NMC	Unspecific, mix	NMC	Unspecific, mix	LFP	LFP	LFP			
Additional treatment to mechanical treatment	unkown	unkown	unkown	unkown	unkown	pyrolysis	pyrolysis	pyrolysis	pyrolysis	vacuum drying			
	Weight (%)												
Mixed metal oxides	10–75 %	-	-	-	-	-	45–50 %	-	-	-	With the exception for LTO and LFP, the various metal oxides trigger a hazardous classification due to their characteristics and the high concentration within the black mass (see **Table 9**)		
Li-oxide	< 10 %	-	-	-	< 70 %*	-	-	-	-	-			
Li-, Ni-oxides	-	-	-	-		-	-	-	-	-			
Li-, Co-oxides	-	1–50 %	-	-		-	-	-	-	-			
Li-, Ni-, Co-, Al-oxides	-	1–50 %	-	-		-	-	-	-	-			
Li-, Ni-, Co-, Mn-oxides	-	1–50 %	60–65 %	30–50 %		≥ 60 %	-	-	-	-			
Li-, Fe-phosphate	-	-	-	-	-	-	-	≥ 60 %	60–70 %	60–70%			
Aluminium	< 10 %	-	1–2 %	< 10 %	< 10 %	< 5 %	10 %	< 5 %	< 5 %	< 5 %	not classified		
Copper powder	< 10 %	-	1–2 %	< 5 %	< 10 %	<5 %	3–4%	< 5 %	< 2.5 %	< 5 %	H411	Aquatic Chronic 2	≥ 2.5 %
Graphite	< 40 %	30–50 %	30 %	25–40 %	10–40 %	< 40 %	–	≤ 40 %	≤ 40 %	30–40 %	not classified		

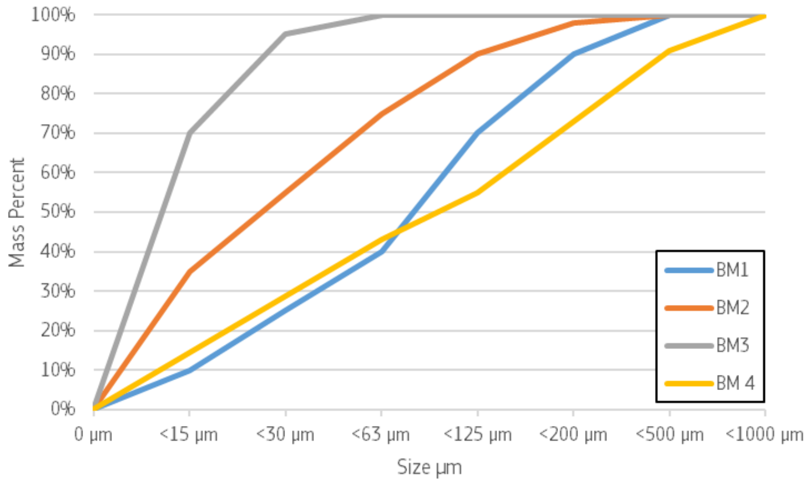
KOH, caustic potash	-	-	-	-	-	< 5 %	-	-	-	-	H302 H314	Acute Tox. 4 Skin Corr. 1A	≥ 25 % ≥ 5 %
Lithium fluoride	-	-	-	-	< 5 %	-	-	< 10 %	< 10 %	-	H302 H319	Acute Tox. 4 Eye Irrit. 2	≥ 25 % ≥ 20 %
PVDF	-	2–7 %	-	-	-	-	-	-	-	< 2 %	H315 H319 H335	Skin Irrit. 2 Eye Irrit. 2 STOT SE 3	≥ 20 % ≥ 20 % ≥ 20 %
Lithium salts (e.g. $LiPF_6$, $LiBF_4$)	-	1–4 %	1–2%	-	< 10 %	-	-	-	-	not detectable	$LiPF_6$ (Specific Target Organ Toxicity) and $LiBF_4$ (Suspected of causing genetic defects) have a concentration limit of ≥ 1 % for waste to be classified as hazardous (see Annex 6, Table 44) Several organic solvents are (highly) flammable. Furthermore, a hazardous classification could be triggered with a concentration of 5–10 %.		
Organic solvents	-	-	-	5–10 %	-	-	-	-	-	not detectable			
Water	10–30%	-	-	-	-	-	-	-	-	-	-		

*lithium carbonate: < 10 %; cobalt oxide: < 30 %; manganese oxide: < 15 %; nickel oxide: < 15 %

Physical properties of black mass from waste lithium-based batteries

To recover a black mass, the battery undergoes several physical treatments as e.g. crushing, shredding, grinding, heat treatment, and density separation. The resulting black mass is a powder and consists of fine particles < 500 µm (see BM 1–3 in **Figure 27**; (Dadé et al., 2022; Donnelly et al., 2022)). The study of (Vanderbruggen et al., 2021) shows, that around 40 % of black mass recovered from NMC and LCO batteries is < 63 µm (90 % is < 500 µm, see BM4 in **Figure 27**). Lithium metal oxides are detectable in all particle sizes. Graphite can be found predominantly in the fraction smaller than 63 µm. An overview on the distribution of particle sizes is given in the following **Figure 27**. For a black mass recovered by one recycler, the particles are in the range from 19 µm to 179 µm (EDI, 2023). LFP black mass from REDUX shows particle sizes D50=12.9 µm and D90 = 52.5 µm[58], obtained with an impact mill.

Figure 27. Mass distribution of particle size of black mass (Dadé et al., 2022; Vanderbruggen et al., 2021)



Chemical compounds of black mass from waste lithium-based batteries and their hazardous properties

As far as the hazard statements for the different compounds are concerned, the components of a black mass have already been outlined in the sections above and are therefore referred to the corresponding **Table 29**.

The lithium salts ($LiPF_6$) in the black mass can react with very small amounts of water, even air humidity. The reaction products are HF, LiF, PF_5, but also Li_2CO_3 can be detected (Arnberger and Höhns, 2023). These chemical compounds have several hazard statement codes assigned, with in some cases low concentration limits (**Table 29**).

Table 29. Chemical compounds that can be formed from $LiPF_6$ in the black mass due to the contact with water / humidity according to CLP (1272/2008)

Chemical compound	CAS No.	Source	Hazard statement code, hazard class and category code	Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)

[58] D represents the diameter of powder particles, and D50 means **a cumulative 50% point of diameter**. D50 is also the average particle size or median diameter. D90, means that 90 % of the particles are smaller than that.

LIF	Lithium fluoride	7789-24-4	REACH registration C&L	H302 H319	Acute Tox. 4 Eye Irrit. 2	≥ 25 % ≥ 20 %	- -	HP 6 HP 4
PF_5	Phosphorus pentafluoride	7647-19-0	Notified C&L	H280 H314 H330	Press. Gas (Liq.) Skin Corr. 1A Acute Tox. 2	- ≥ 1 % and < 5 % ≥ 0.1 %	- - -	- HP 4 HP 6
HF	Hydrogen fluoride	7664-39-3	Multiple harmonised classifications	H300 H310 H314 H330	Acute Tox. 2 Acute Tox. 1 Skin Corr. 1A Acute Tox. 2	≥ 0.1 % ≥ 0.25 % ≥ 1 % and < 5 % ≥ 0.1 %	- - - -	HP 6 HP 6 HP 4 HP 6
Li_2CO_3	Lithium carbonate	554-13-2	REACH registration C&L	H302 H319	Acute Tox. 4 Eye Irrit. 2	≥ 25 % ≥ 20 %	- -	HP 6 HP 5

Recommendation on classification of lithium-battery based black mass and recommendation for new waste codes

Black mass from metal oxide containing lithium-based batteries

As elaborated in section 4.2.1 (lithium waste batteries) the cathode material of lithium-based batteries is relevant for the classification as hazardous. In mechanical recycling processes, the various battery chemistries as e.g. LCO, LMO, NMC, NCA and LTO enter the process as a mixture, meaning that the black mass consists of a mix of the various metal oxides. In case these batteries undergo only a mechanical recycling, in which the casing and other parts (paper, plastic) of the battery cell are removed, the percentage share of these chemical compounds further increases, meaning that also the black mass from lithium ion batteries has to be classified as hazardous.

In case the lithium-based batteries undergo only mechanical treatment, the black mass contains the chemical compounds from the organic solvents (lithium salts and organic solvents) and binder. For the lithium salts a hazardous classification is already triggered with low concentration of ≥ 1 % and could be exceeded as the lithium salts can be detected at concentration ≥ 1 %.

Some technological approaches are capable of removing organic compounds with a thermal treatment, but even if these organic compounds can be removed, the black mass is still classified as hazardous, as the thermal treatment has no effect on the metal oxides.

As highlighted in **Table 28**, black mass contains copper in concentration from 1 % to less than 10 %, originating from the shredded cupper foil. Granulated copper, specifically granulated copper with a particle length from 0.9 to 6.0 mm and a particle width from 0.494 to 0.949 mm has the hazard statement code H411 (Aquatic Chronic 2, toxic to aquatic life with long lasting effects) with a concentration limit of ≥ 2.5 %.

Furthermore, the draft Commission Delegated Regulation[59], which is envisaged to amend Annex VI of CLP (22nd adaptation to technical progress), contains a proposal, based on an opinion[60] by the Risk Assessment Committee of the European Chemicals Agency, to classify metallic copper powder, having a specific surface area > 0.67 mm^2/mg, as H410. As indicated in the referred opinion, particles with a diameter below 1 mm are expected to meet the surface area requirements for classification. Consequently, scientific evidence indicates that, following the envisaged future classification of metallic copper powder under CLP, an aquatic chronic hazard classification would be applicable to waste containing powdered metallic copper in amounts greater than 0.25%.

Taking due account of the above and given the particle size distribution for black mass indicates that the particle size of the copper present therein is even lower (90-100 % smaller than 0.5 mm) and that for some black masses the maximum particle size can be as low as 0.2 mm, it can be concluded that black mass from metal oxide containing lithium-based batteries can be classified as hazardous, amongst other reasons, based on the copper powder content (Ecotoxic HP14).

Black mass from lithium iron phosphate

The black mass from LFP waste batteries consist mainly of the components lithium iron phosphate and graphite, both do not have any hazard statement code. Lithium fluoride with the hazard statement codes H302 (Acute Tox. 4) and H319 (Eye Irrit. 2) can be detected in such concentration (< 10 %), that no hazard classification is applicable (H302: concentration limit ≥ 25 %; H319: concentration limit ≥ 25 %).

Waste LFP batteries can also contain the lithium salts and organic solvents that were originally contained in the LFP battery. The data available to date stem from thermally treated black mass (BM 8 and 9) and therefore the organic compounds cannot be detected. For the BM 10, the PVDF concentration is too low to trigger a hazardous classification and lithium salts or organic solvents cannot be detected. However, it is unclear how this black mass was treated and if for example a thermal treatment resulted in the removal of the lithium salts or organic solvents.

With regard to copper, the black mass from LFP also contains copper particles, in the form of a fine powder, at concentrations that can reach 2.5 % or 5.0 %, respectively, for the two LFP black masses for which information is available.

As indicated above and given granulated copper is currently assigned hazard statement code H411 (Aquatic Chronic 2, toxic to aquatic life with long lasting effects), with a concentration limit of ≥ 2.5 %, and that a proposal currently exists, based on an ECHA opinion, to classify metallic copper with a specific surface area > 0.67 mm^2/mg, as H410, resulting in an applicable concentration limit for waste of 0.25 % black mass from LFP batteries would be classified as hazardous waste and HP14, at least, due to the presence of powdered metallic copper.

Furthermore, regarding the chemical composition of LFP black mass, the stakeholder commented, that in practice a strict separation of LFP from other lithium-based waste batteries is impossible along the whole collection and recycling chain. Therefore, it is reasonable to assume that even a "pure" LFP black mass will contain chemical compounds from other lithium-based batteries with hazardous properties.

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition and its variability, the classification of the chemical compounds contained the JRC proposes to **classify all**

[59] Draft Commission Delegated Regulation amending Regulation (EC) No 1272/2008 of the European Parliament and of the Council as regards the harmonised classification and labelling of certain substances. CARACAL, 24 January 2024. Publicly available at: https://circabc.europa.eu/ui/group/a0b483a2-4c05-4058-addf-2a4de71b9a98/library/79250b36-e6a2-42cf-92e7-5f090693b519?p=1&n=10&sort=modified_ASC

[60] Opinion of 1 December 2022 concerning copper. ECHA. https://echa.europa.eu/documents/10162/90cccc64-d836-972d-bbc3-99155a9c82e2

black mass from waste lithium-based batteries and lithium-based battery manufacturing waste as absolute hazardous.

Recommendation for new waste codes for black masses from lithium-based batteries in the LoW:

The JRC proposes to introduce a new waste code for lithium-based battery black mass in the chapter 19, sub-chapter "19 12 wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified".

- 19 12 14* Intermediate fraction from the thermal/mechanical treatment of waste lithium-based batteries and lithium-based battery manufacturing waste containing a mixture of electrode materials

4.3.2.2. Intermediates from hydrometallurgical black mass treatment

As described in Chapter 2, several intermediates as e.g. mixtures of precipitated metal salts (hydroxides or sulphates) can be produced in a hydrometallurgical recycling process. It is important to note that the impurity content at this level of recycling is still too high to allow a direct use as a product in a production process. Therefore, further recycling and/or refining steps are necessary.

Physical properties of precipitated metal salts from black mass treatment

When the dissolved salts precipitate from the liquid phase, water-insoluble compounds are formed which are available in powder form after drying. A detailed list of the potentially precipitated salts with hazardous characteristics is given in Annex 11 (**Table 49**).

Chemical compounds of precipitated metal salts from black mass treatment

The chemical composition of this intermediate is similar to black mass, but the graphite and in many cases the lithium is removed. This leads to an increase in the concentration of e.g. Ni, Co and Mn in the intermediates. These intermediates typically contain Ni in the form of nickel (II) sulphate hexahydrate or nickel nickel (II) hydroxide, Cobalt is present as cobalt (II) sulphate or cobalt (II) hydroxide and/or Manganese as manganese (II) sulphate or manganese hydroxide (Ma et al., 2020; Mazur and Penha, 2023). No data is available for the concentration of these chemical compounds in the precipitated salts. Considering the removal of graphite during the treatment, the concentration of the metals can be assumed to be higher than in the black mass that is fed to the hydrometallurgical process.

Recommendation on classification of precipitated metal salts and recommendation for new waste codes

Even though the concentration of the various metal salts is not known, it can be assumed that their concentration is clearly higher than in the black mass. **Table 49** shows that all chemical compounds are associated to different hazardous statements and for many of them the concentration limit for a hazardous classification is very low, especially for those with carcinogenic or mutagenic properties (e.g. limit value of ≥ 0.1 % for H350i (Carc. 1B) or for H360Fd ≥ 0.3 % (Repr. 1B). Therefore, a classification as absolute hazardous is proposed.

Based on the information known to date on the qualitative composition and the classification of the chemical compounds contained, the JRC proposes to **classify all precipitated metal salts from lithium containing black mass as hazardous.**

Recommendation for new waste codes for precipitated metal salts from lithium-based batteries in the LoW:

A new waste code is proposed to be introduced under sub-chapter 19 02 "Wastes from physico/chemical treatments of waste":

- 19 02 12* Solid salts and solution containing heavy metals from waste battery recycling

4.3.2.3. Alloys from pyrometallurgical lithium-based waste battery recycling

An alloy is the metallic phase from the pyrometallurgical lithium-based waste battery recycling and is defined[61] as **a substance that is formed from the combination of two or more metals**. Alloys can also be formed from combinations of metals and other elements.

Physical properties of alloys from waste lithium-based batteries

In an alloy, the atoms are joined by metallic bonding rather than by covalent bonds typically found in chemical compounds. The metallic bonding accounts for many physical properties, such as density, hardness but also corrosion resistance, meaning that the metals within alloys are strongly bound.

Chemical compounds of alloy from waste lithium-based batteries and their hazardous properties

Alloys from pyrometallurgical lithium-based waste battery recycling are constituted mainly by the metals Cu, Co, Fe, Ni, and also Mn. As for black mass, the composition of the alloy can vary significantly depending on the type of lithium-based battery entering a recycling process and the process conditions (e.g. slag former, temperature). For example Alloy 3 and 4 show high Mn concentration compared to Alloy 1, mainly based on the slag former used (MnO-SiO_2-Al_2O_3 for Alloy 3 and 4). In some cases, beside Li-based batteries also other types of batteries are co-processed (e.g. NiMH) and in some cases the batteries are only a small part of the general input materials to the smelting process (e.g. Umicore). **Table 30** illustrates the composition of different alloys and its variability (Brückner et al., 2020; Elwert et al., 2012; Ren et al., 2016; REN et al., 2017; Umicore, 2016; Windisch-Kern et al., 2021).

Table 30. Chemical compounds and % share of alloys recovered from pyrometallurgical lithium-based batteries

	Alloy 1	Alloy 2	Alloy 3	Alloy 4	Alloy 5
Input	Various Li-based batteries/NiMH batteries	Various Li-based batteries/NiMH batteries	Mixed spent Li-based batteries (with Al cans and polymer batteries)	Mixed spent Li-based batteries (with Al cans and polymer batteries)	AM/NCA/NMC
Temperature	1450 °C	1450 °C	1475 °C	1550 °C	1550 °C
Slag former	CaO, SiO_2	CaO, SiO_2	MnO-SiO_2-Al_2O_3	MnO-SiO_2-Al_2O_3	No, only graphite bed
SiO_2	-	-	-	3 %	-
CaO	-	-	-	0.3 %	-
Al_2O_3	-	-	-	-	0.1–3.7 %
FeO	-	-	-	-	-
Fe	35 %	28 %	10.85 %	26–38 %	-
MgO	-	-	-	0.015 %	-
Li_2O	-	-	-	-	-
Co	25 %	33 %	24.40 %	14–18.5 %	8–36 %

[61] Article 3(41) of REACH defines alloy as: "a metallic material, homogenous on a macroscopic scale, consisting of two or more elements so combined that they cannot be readily separated by mechanical means."

Cu	25 %	22 %	21.80 %	13–17 %	-
Mn	4 %	-	30.13 %	36 %	28 %
Ni	10 %	11 %	5.05 %	5–6 %	34–92 %

Table 31. Chemical compounds of alloys from pyrometallurgical recycling of lithium ion batteries with assigned hazard identification according to CLP (Regulation (EC) No. 1272/2008)

Chemical compound	Concentration by weight (%)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Cu (massive)	13–25 %	–[62]	-	-	-	-	-	-
Co	14–25 %	7440-48-4	Harmonised C&L	H317 H334 H341 H350 H413 H360F	Skin Sens. 1 Resp. Sens. 1 Muta. 2 Carc. 1B Aquatic Chronic 4 Repr. 1B	≥ 10 % ≥ 10 % ≥ 1.0 % ≥ 0.1 % ≥ 25 % ≥ 0.3 %	Y Y Y Y N Y	HP13 HP13 HP11 HP7 HP14 HP10
Fe	11–38 %	7439-89-6	REACH registration C&L	-	not classified	-	-	-
Mn	4 %	7439-96-5	REACH registration C&L	-	not classified	-	-	-
Ni	5–10 %	7440-02-0	Multiple harmonised classifications	H317 H351 H372	Skin Sens. 1 Carc. 2 STOT RE 1	≥ 10 % ≥ 1.0 % ≥ 1 %	N Y Y	HP13 HP7 HP5

Recommendation on classification of alloys from lithium-based waste battery recycling and of new waste codes

Cu, Co and Ni are present in alloys in such concentrations that the concentration limits for the categorisation as hazardous waste would be clearly exceeded. However, according to the Commission notice on technical guidance on the classification of waste (2018/C 124/01), for alloys it needs to be considered that the Annex of Decision 2000/532/EC specifies that for waste constituted by **pure metal alloys, these are specifically exempt from the classification as hazardous:**

'The concentration limits defined in Annex III to Directive 2008/98/EC do not apply to pure metal alloys in their massive form (not contaminated with hazardous substances). Those waste alloys that are considered as hazardous waste are specifically enumerated in this list and marked with an asterisk (*)'

[62] For copper in a massive form, no entry exists.

The List of Waste lists a number of massive metallic wastes constituted by bulk metals or alloys resulting from different processes, for example:

1) demolition (chapter 17: Construction and demolition wastes (including excavated soils from contaminated sites); sub-chapter 17 04, metals (including alloys)) contains waste codes for different metals including their alloys. The metal waste codes are classified as **absolute non-hazardous** even though they contain metals as e.g. lead, copper or zinc that are considered as hazardous (**Table 31**).
2) wastes from shredding of metal-containing wastes (subchapter 19 10) - 19 10 01 iron and steel waste; 19 10 02 - non-ferrous waste.
3) wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified (subchapter 19 12) - 19 12 02 - ferrous metal; 19 12 03 non-ferrous metal.

None of the above waste codes would however be applicable to waste alloys resulting from a thermal process. Similarly, no applicable waste streams constituted specifically by alloys are described under Chapter 10 (wastes from thermal processes) given the purified bulk metals and alloys resulting from primary and secondary thermos-metallurgical processes described in this chapter are generally the final output of the smelting process and no longer considered to be waste. In the case of alloys described in this section, these are understood to require further processing, still as waste.

Recommendation on classification of alloy from lithium-based waste batteries

Based on the aspect considered that **pure metal alloys are specifically exempt from the classification as hazardous,** the JRC proposes to classify alloys recovered from waste lithium-based batteries and lithium-based batteries manufacturing waste as non-hazardous.

Recommendation for new waste codes for precipitated metal salts from lithium-based batteries in the LoW:

The JRC proposes to adapt the EU LoW with a new absolute non-hazardous entry for alloys from all lithium-based batteries:

- 10 08 27 Alloys from waste battery recycling (in massive form)

4.3.2.4. Slag from pyrometallurgical waste lithium-based battery recycling

(Latini et al., 2022) highlight, that Li, Si, Al, Mn, Ca and part of Fe are contained in the slag fraction in oxidized state (metal oxides). Due to its low-quality, the slags are typically addressed to markets as e.g. construction material additive.

Physical properties of slag from waste lithium-based batteries

Slags are a by-product formed during the smelting, refining, or manufacturing of metals and other materials. It consists mainly of the non-metallic components, including impurities, oxides, and other compounds that are separated and removed during the processing of ores and metals. Slag is typically a glassy and/or granular material

Constituents of slag from waste lithium-based batteries and their hazardous properties

Slag from pyrometallurgical lithium-based waste battery recycling are constituted mainly of SiO_2, CaO, Al_2O_3 and Li_2O. Metals such as Cu, Co, Ni can be detected only in low concentration. The composition of slags can vary significantly depending on the type of lithium-based battery entering a recycling process and the process conditions (e.g. slag former, temperature). For example Alloy 5 show high Fe concentrations compared to the other slags, resulting from the slag former used (Fe-SiO_2-Al_2O_3). In some cases, beside Li-based batteries also other types of batteries are co-processed (e.g. NiMH) and in some cases the batteries are only a small part of the general input materials to the smelting process (e.g. Umicore). **Table 32** illustrates the composition of different slags and its variability (Brückner et al., 2020; Elwert et al., 2012; Ren et al., 2016; REN et al., 2017; Umicore, 2016; Windisch-Kern et al., 2021).

It should be noted that slags are a waste resulting from the pyrometallurgical processing of natural ores or the recycling of man-made materials. During smelting, molten metal is separated from the impurities as slag is formed. Consequently, intermediate fractions resulting from mechanical and or thermal treatment (with treatment temperature below the ash melting point, e.g. pyrolysis), such as so-called "black masses", that do not result from a smelting process, should not be classified as slags.

Table 32. Chemical compounds and % share of slags recovered from pyrometallurgical lithium-based batteries

	Slag 1	Slag 2	Slag 3	Slag 4	Slag 5	Slag 6
Input	Various Li-based batteries/NiMH batteries	Various Li-based batteries/NiMH batteries	Mixed spent Li-based batteries (with Al cans and polymer)	Mixed spent Li-based batteries (with Al cans and polymer)	Spent Li-based batteries with sizes of 60 mm × 43 mm × 5 mm	AM/NCA/NMC
Temperature	1450 ◦C	1450 ºC	1475 ºC	1550 ºC	1450 ºC	1550 ºC
Slag former	CaO, SiO_2	CaO, SiO_2	MnO-SiO_2-Al_2O_3	MnO-SiO_2-Al_2O_3	Fe-SiO_2-Al_2O_3	No, only graphite bed
SiO_2	21.6 %	30 %	15–21 %	21.93 %	30–41.2 %	-
CaO	22 %	28 %	6–9 %	-	4–6 %	-
Al_2O_3	44 %	29 %	17–24 %	30.39 %	14–21.5 %	-
Al	-	-	-	-	-	2.5-7.5 %
FeO	-		0.11–0.84 %	-	24–41 %	-
Fe	0.17 %	0.90 %	-	0.38 %	-	-
MgO	-	-	-	-	-	-
Li_2O	8.40 %	-	2.63 %	2.83 %	-	-
Li						4.5-9.8 %
MnO	2 %	-	42–50 %	33.01 %	2.5–3.5 %	-
Mn	-	-	-	-	-	0.15 %
Co	0.10 %	< 0.05 %	-	0.12 %	0.04–0.12 %	0.03–3 %
Ni	0.05 %	< 0.05 %	-	0.03 %	0.11–0.13 %	0.1–4.3 %
Cu	0.08 %	< 0.05 %	-	0.18 %	-	-
S	-	-	-	-	0.4–0.45 %	-

For slags, the major metallic phase that is found is calcium tephroite $(Mn,Ca)_2SiO_4$ and galaxite ($MnAl_2O_4$) (Ren et al., 2016) as well as Fayalite (Fe_2SiO_4) and Hercynite ($FeAl_2O_4$) (REN et al., 2017).

Table 33. Chemical compounds of slags from pyrometallurgical recycling of lithium-based waste batteries with hazard identification according to CLP (1272/2008)

Chemical compound	Weight (%)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
SiO_2	15–40 %	7631-86-9	REACH registration C&L	-	not classified	-	-	-
SiO_2 (Quarz)	15–40 %	14808-60-7	REACH registration C&L	-	not classified	-	-	-
CaO	6–8 %	1305-78-8	REACH registration C&L	H315 H335	Skin Irrit. 2 STOT SE 3	≥ 20 % ≥ 20 %	°Y °Y	HP4 HP5
Al_2O_3	14–44 %	1344-28-1	REACH registration C&L	-	not classified	-	-	-
FeO	0.1–44 %	1332-37-2	Notified C&L	-	not classified	-	-	-
MnO	2–50 %	1313-13-9	Harmonised C&L	H302 H332	Acute Tox. 4 Acute Tox. 4	≥ 25 % ≥ 22.5 %	°Y °Y	HP6 HP6
Li_2O	2.6–8.4 %	12057-24-8	REACH registration C&L	H314 H331	Skin Corr. 1B Acute Tox. 3	≥ 5 % ≥ 3,5 %	°Y °Y	HP8 HP6
Co	< 0.05–0.12 %	7440-48-4	Harmonised C&L	H317 H334 H341 H350 H413 H360F	Skin Sens. 1 Resp. Sens. 1 Muta. 2 Carc. 1B Aquatic Chronic 4 Repr. 1B	≥ 10 % ≥ 10 % ≥ 1.0 % ≥ 0.1 % ≥ 25 % ≥ 0.3 %	N N N °Y N N	HP13 HP13 HP11 HP7 HP14 HP10
Ni	< 0.05–0.11 %	7440-02-0	Multiple harmonised classifications	H317 H351 H372	Skin Sens. 1 Carc. 2 STOT RE 1	≥ 10 % ≥ 1.0 % ≥ 1 %	N N N	HP13 HP7 HP5
Cu	< 0.05–0.18 %	7440-50-8[63]	Harmonised C&L	-	-	-	-	-
S	0.4–0.45 %	7704-34-9	Harmonised C&L Notified C&L	H315 H228	Skin Irrit. 2 Flammable solid	≥ 20 % -	N -	HP4 -

Recommendation on classification of slags from lithium-based waste battery recycling and recommendation for new waste codes

For a potential classification of slags from pyrometallurgical lithium-based waste battery recycling as hazardous or non-hazardous, the content of CaO, MnO and Li_2O are the decisive factors (**Table**

[63] not classified due to presence in massive form

40). Depending on the technology and the slag former used, the CaO, MnO or Li_2O concentration could exceed the concentration limit value for the hazardous statement codes H302, H314, H315, H318, H331 H332, and H335.

For example in Belgium, slags recovered from lithium-based batteries are assigned to the non-hazardous waste code 10 08 09 (other slags) However, stakeholders commented, that a new hazardous waste code, in the form of a mirror entry could be implemented to cover slags with hazardous properties.

Recommendation on classification of slags from waste lithium-based batteries recycling

Based on the information known to date on the qualitative composition, the classification of the chemical compounds contained and the stakeholder comments to implement a mirror entry for the slags, JRC proposes to have a **mirror entry for slags recovered from waste lithium-based batteries.**

Recommendation for new waste codes for slags from waste lithium-based batteries recycling in the LoW:

The JRC proposes to adapt the EU LoW with a new non-hazardous and hazardous mirror entries for slags from all waste lithium-based batteries in chapter 10, sub-chapter 10 08 "wastes from other non-ferrous thermal metallurgy":

- 10 08 21* slags from waste lithium-based battery recycling containing hazardous substances
- 10 08 22 slags from waste lithium-based battery recycling other than those mentioned in 10 08 21.

4.3.2.5. Other intermediate fractions from mechanical recycling of waste lithium-based batteries

The separation of ferrous, non-ferrous metal fractions and foil as well as plastic is carried out through state of the art technologies (e.g. sieve, magnet, eddy current, density separation in air and liquid). The recovery of graphite or electrolytes has not been implemented on a large scale yet. The following list gives an overview on those intermediate and their current assignment in the LoW (in parenthesis):

- Steel fraction[64] (19 12 02: ferrous metal)
- Aluminium fraction (19 12 03: non-ferrous metal)
- Plastics (19 12 04: plastic and rubber)
- Electronic parts (several waste codes from the sub-chapter 16 02: wastes from electrical and electronic equipment, e.g. 16 02 14 discarded equipment other than those mentioned in 16 02 09 to 16 02 13; 16 02 15* hazardous components removed from discarded equipment; 16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15)
- Electrolyte (16 06 06* separate collected electrolyte from batteries and accumulators)
- Graphite (19 12 09 minerals (for example sand, stones))
- Copper and aluminium foils (19 12 03: non-ferrous metal)

At this point it should be noted that, depending on the process, clearly detectable concentrations of black mass or electrolytes can be found in these fractions, which in turn can result in classification as hazardous. This must be verified on a case-by-case basis.

Based on the information known to date, the JRC proposes **not to amend the LoW for the other intermediate fractions**, as they are already well covered by the current List of Waste.

[64] For ferrous metal various waste codes exists in the EU LoW. However, ferrous metal in the sub-category 19 12 wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified) seems most appropriate.

4.3.3. Intermediate fractions from lithium-based battery manufacturing waste recycling

Concentrates from NCA, NMC and LFP battery manufacturing waste recycling

One stakeholder provided detailed information on intermediate fractions from mechanical recycling of lithium-based battery manufacturing waste (see **Annex 12**, **Table 50**).

The input to the mechanical recycling is a mix of e.g. dried slurry, cuttings and failed electrodes. The outputs are an Al-, Co-mixture, a Ni-, Co-concentrate (from NCA and NMC), a LFP-concentrate and a light fraction (mainly polymers). The Al-, Co-mixture is currently associated to the waste code 19 12 03 (non-ferrous metal). For the other outputs, the waste codes currently applied are unspecific (19 12 11*: other wastes (including mixtures of materials) from mechanical treatment of waste containing hazardous substances and 19 12 12: other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11).

Recommendation on classification of certain concentrates recycled from lithium-based battery manufacturing waste

Due to the high concentration of Al-Co-Li-Ni-oxide and Co-Li-Mn-Ni-oxid, the concentrates recycled from NCA and NMC manufacturing waste have to be classified as hazardous. For the LFP concentrate, the lithium iron phosphate itself is not classified as hazardous. However, the concentrate contains Al and Co in concentrations below 5 % for both of the elements. The hazard classification of Al depends on its physical characteristics. As powder, the hazard statement codes are H250 (catches fire spontaneously if exposed to air) and H261 (in contact with water releases flammable gas) could apply. The limit value for H261 is 0.1 %. As the aluminium is present in a powdery form in the concentrates, also the LFP concentrates need to be classified as hazardous. Furthermore, all concentrates contain copper in a powder form (≤ 5 %). For copper, the limit value for H411 is ≥ 2.5 %. It is highly likely, that this limit value is exceed, triggering a hazardous classification (HP4).

Recommendation on classification of concentrates recycled from lithium-based battery manufacturing waste

Based on the information known to date on the qualitative and quantitative composition (including the variability) and the classification of the chemical compounds contained, the JRC proposes to **classify all mechanical recovered concentrates from lithium-based battery manufacturing waste as absolute hazardous.**

Recommendation for new waste codes for concentrates recycled from lithium-based battery manufacturing waste:

The JRC proposes to assign this waste to:

- 19 12 14* Intermediate fraction from the thermal/mechanical treatment of waste lithium-based batteries and lithium-based battery manufacturing waste containing a mixture of electrode materials.

4.3.4. Intermediate fractions from nickel-based waste battery recycling

As elaborated in section 2.1.4.3, various intermediate fractions are produced from the mechanical and pyrometallurgical recycling of waste NiMH- and Na-$NiCl_2$-batteries. In some cases, mechanically recycled materials (e.g. Ni or Ni-Fe briquettes) are used in the pyrometallurgical process to produce stainless steel in the following sections the physical- and chemical properties, the weight distribution and the variability of substances and chemical compounds of black mass (section 4.3.3.2) and other material flows from mechanical recycling (section 4.3.3.2) are presented. The pyrometallurgical recycling route is not under scope, as the nickel waste batteries are directly transformed into a product (steel/stainless steel). Based on this information, the hazard determination was performed and a hazard classification is proposed.

4.3.4.1. Black mass from mechanical waste NiMH battery recycling

To recover black mass, the NiMH batteries undergo several physical treatments as e.g. crushing, shredding, and separation.

Physical properties of black mass from waste NiMH batteries

The NiMH batteries undergoes several physical treatments as e.g. crushing, shredding, and separation to recover a black mass. The black mass is a mixture of the cathode and anode material containing high concentration of nickel hydroxide. The black mass is a powder and consists of fine particles, all smaller than 1 mm. Around 50 % of black mass recovered from NiMH batteries is even < 63 µm (Ebin et al., 2018). According to (Ebin et al., 2018) the anode and cathode active materials that are hydrogen storage alloy and nickel hydroxide are mainly detected in finer size fraction of the black mass.

Constituents of black mass from waste NiMH batteries and their hazardous properties

The resulting black mass is a mixture of the cathode and anode material containing high concentration of nickel hydroxide (Ni(OH)).

Recommendation on classification of black mass from waste nickel-based battery recycling and recommendation for new waste codes

Operators that recycle NiMH batteries assign the mixture containing the nickel hydroxide as hazardous (19 12 11* other wastes (including mixtures of materials) from mechanical treatment of waste containing hazardous substances).

With mechanical recycling, the chemical compounds in the cathode and anode of a NiMH battery with hazardous properties as e.g. nickel (metallic) but also nickel oxide hydroxide (NiO(OH)) even increase.

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition (including the variability) and the classification of the chemical compounds contained, the JRC proposes to **classify black mass recovered from waste nickel-based battery (NiMH and Na-$NiCl_2$) and nickel-based battery manufacturing waste as absolute hazardous.**

Recommendation for new waste codes for black masses from waste nickel-based batteries in the LoW:

The JRC proposes to assign this waste to:

- 19 12 15* Intermediate fraction from the thermal/mechanical treatment of waste nickel-based batteries and nickel-based battery manufacturing waste containing a mixture of electrode materials

4.3.4.2. Other intermediate fractions from mechanical waste NiMH battery recycling

Other intermediates from the mechanical recycling of waste NiMH batteries are nickel-iron fractions and a plastic fraction. According to REDUX, the nickel-iron fractions and the plastic are classified as non-hazardous waste (19 12 02: ferrous metal and 19 12 04: plastic and rubber).

Precipitated salts from waste Na-$NiCl_2$ battery recycling

During mechanical recycling the **Na-$NiCl_2$ batteries** are shredded and the soluble components such as $NiCl_2$, NaCl, and NaAlCl are leached out. These soluble components are then the subsequently precipitated as NaCl and NaAlCl from the solution. NaAlCl is classified as H314 with low concentration limits for waste to be classified as hazardous (≥ 5 %).

Recommended hazard classification:

Based on the information known to date on the qualitative composition and the classification of the chemical compounds contained, the JRC proposes to **classify the precipitated metal salts from nickel containing batteries as hazardous.**

Recommendation for new waste codes for precipitated metal salts from nickel-based batteries in the LoW:

The JRC proposes to introduce a new waste codes in the chapter 19, sub-chapter “19 02 wastes from physico/chemical treatments of waste (including dechromatation, decyanidation, neutralisation)”

- 19 02 12* Solid salts and solution containing heavy metals from battery recycling

4.3.4.3. Classification of slags from nickel-based waste battery recycling and recommendation for new waste codes

In most cases, the pyrometallurgical recycling route is not battery-specific, as the nickel waste batteries are directly transformed into a product (steel/stainless steel) or yield other non-battery specific wastes. However, some processes may produce battery-specific intermediates from nickel-based waste batteries or battery manufacturing waste, hence the following recommendation.

Recommendation on classification of slags from waste nickel-based batteries recycling

Based on the information known to date on the qualitative composition, the classification of the chemical compounds contained and the stakeholder comments to implement a mirror entry for the slags, JRC proposes to have a **mirror entry for slags recovered from waste nickel-based batteries.**

Recommendation for new waste codes for slags from waste nickel-based batteries recycling in the LoW:

The JRC proposes to adapt the EU LoW with new non-hazardous and hazardous mirror entries for slags from all waste nickel-based batteries in chapter 10, sub-chapter 10 08 “wastes from other non-ferrous thermal metallurgy”:

- 10 08 23* slags from waste nickel-based battery recycling containing hazardous substances
- 10 08 24 slags from waste nickel-based battery recycling other than those mentioned in 10 08 23.

4.3.5. Intermediate fractions from alkaline-based waste battery recycling

Black mass from mechanical waste alkaline-based battery recycling

Physical properties of black mass from waste alkaline-based batteries

Similar to other black masses recovered from waste Li- or Ni batteries, the black mass recovered from waste alkaline-based batteries are a fine powder. The average particle size of alkaline black mass is 250–500 µm and the metals are known to be concentrated on the smaller fractions (Tracegrow, 2019).

Chemical compounds of black mass from waste alkaline-based batteries and their hazardous properties

As described in section 4.2.5, zinc oxide (ZnO) and di-manganese tri-oxide (Mn_2O_3) are formed during the use of an alkaline battery. In a mechanical recycling process the alkaline-based batteries do not undergo a chemical change, so the black mass is defined by the chemical compounds found in the waste alkaline-based batteries (see section 4.1.4).

Recommendation for the targeted amendment of the LoW for waste alkaline-based battery based black mass and recommendation for new waste codes

As elaborated in section 4.2.4 (waste alkaline-based batteries) the cathode material of alkaline-based batteries (MnO_2) is relevant for the classification as hazardous waste. As these batteries undergo only a mechanical recycling, in which the casing and other parts (paper, plastic) of the battery are removed, the percentage share of e.g. MnO_2 even increases.

Furthermore, during the life-time of an alkaline battery, the overall reactions result in the formation of ZnO and Mn_2O_3. ZnO is assigned hazard statement code H410 (Aquatic chronic 1) - very toxic to aquatic life with long lasting effects. The concentration limit of the individual substance or sum of substances for waste containing these substances to be classified as hazardous HP 14 (Ecotoxic) is ≥ 0.25 % (EC, 2018). Particularly ZnO (25-45 %) exceeds this limit value significantly.

Recommendation for the targeted amendment of the LoW

Based on the information known to date on the qualitative and quantitative composition (including the variability) and the classification of the chemical compounds contained, the JRC proposes to classify **black mass from waste alkaline-based batteries and alkaline-based battery manufacturing waste as absolute hazardous**.

Recommendation for new waste codes for black masses from waste alkaline-based batteries in the LoW:

The JRC proposes to adapt the EU LoW with a new hazardous waste code:

- 19 12 16* Intermediate fraction from the thermal/mechanical treatment of waste alkaline-based batteries and alkaline-based battery manufacturing waste containing a mixture of electrode materials

4.3.6. Intermediate fractions from waste zinc-based battery recycling

Black mass from mechanical waste zinc-based battery recycling

Physical properties of black mass from waste zinc-based batteries

Similar to other black masses recovered from waste Li- or Ni batteries, the black mass recovered from waste zinc-based batteries are a fine powder.

Chemical compounds of black mass from waste zinc-based batteries and their hazardous properties

As elaborated in section 4.2.5 (zinc waste batteries) the waste zinc-based batteries are classified as hazardous due to the metallic zinc, the chemical zinc compounds and manganese dioxide (MnO_2). As these batteries undergo only a mechanical recycling, in which the casing and other parts (paper, plastic) of the battery are removed, the percentage share of the hazardous components increases.

Recommendation on classification of waste zinc-based battery black mass and recommendation for new waste codes

Recommended hazard classification:

Based on the information known to date on the qualitative and quantitative composition (including the variability) and the classification of the chemical compounds contained, the JRC proposes to **classify black mass from waste zinc-based batteries and zinc-based battery manufacturing waste as absolute hazardous.**

Recommendation for new waste codes for black masses from waste zinc-based batteries in the LoW:

The JRC proposes to adapt the EU LoW with a new hazardous waste code:

- 19 12 17* Intermediate fraction from the thermal/mechanical treatment of waste zinc-based batteries and zinc-based batteries manufacturing waste containing a mixture of electrode materials

4.3.7. Intermediate fractions from sodium-based waste battery recycling

As no waste sodium-based batteries are currently recycled, no statements can be made about possible recycling outputs. Based on the information currently available on sodium-based batteries and to ensure a consistent approach with that proposed for other categories, the JRC formulates the following recommendation:

Recommended hazard classification:

The JRC proposes to classify intermediate fractions from the thermal and mechanical recycling from waste sodium-based batteries and sodium-based battery manufacturing waste as absolute hazardous.

Recommendation for new waste codes for mixtures of electrode material from waste sodium-based batteries and sodium-based battery manufacturing waste in the LoW:

The JRC proposes to adapt the EU LoW with a new hazardous waste code:

- 19 12 18* Intermediate fraction from the thermal/mechanical treatment of waste sodium-based batteries and sodium-based battery manufacturing waste containing a mixture of electrode materials

4.3.8. Intermediate fractions from other battery recycling

Recommendation for new waste codes for slags from other types of batteries recycling in the LoW:

For reasons of consistency and completeness, the JRC proposes to adapt the EU LoW with new non-hazardous and hazardous mirror entries for slags from all other batteries not captured elsewhere (taking due account of the use of code 10 04 01 for lead slags) in chapter 10, sub-chapter 10 08 "wastes from other non-ferrous thermal metallurgy":

- 10 08 25* Slags from other waste battery recycling containing hazardous substances except 10 04 01
- 10 08 26 Slags from other waste battery recycling other than those mentioned in 10 08 25.

Recommendation for new waste codes for intermediates from other types of batteries recycling in the LoW:

For reasons of consistency and completeness, the JRC proposes to adapt the EU LoW with a new hazardous code:

- 19 12 19* Intermediate fraction from the thermal/mechanical treatment of waste batteries and battery manufacturing waste containing a mixture of electrode materials, not otherwise specified in 19 12 13 to 19 12 18

4.4. Potential impact of recommended waste classification

4.4.1. Do-nothing scenario

Under an assumption that the List of Waste entries for batteries do not change, the current codes listed in Table 1 will continue to apply. This will lead to an exacerbation of the current issues, in particular the following three major problems:

1. Most commercially relevant battery types (market data illustrated in section 1.3) will fall under the catch-all 'other' category (16 06 05) rather than specific codes. This will create confusion and prevent any proper monitoring of the waste.
2. The above mentioned 16 06 05 category is absolute non-hazardous, which means that by default any battery not falling under the other codes is considered non-hazardous. The analysis carried out in this project demonstrates that this is generally not the case. Most battery waste would then be able to circulate as non-hazardous waste, increasing the likelihood for the occurrence of adverse events (e.g. pollution due to cargo spill).
3. To address the above, Member States will continue to develop more appropriate waste codes under national legislation, leading to a fragmentation of the internal market and complicating trans-frontier shipments even further, as well as introducing unfair treatment of operators in different jurisdictions.

Therefore, from the perspective of the technical analysis developed herein, the assumption of no action is not a recommended course of action.

4.4.2. Impact of "hazardous" classification

As alluded to in the introductory section, the hazardous nature of waste has impacts on the way it is considered under EU waste legislation, notably the WFD and WSR, but also in the legislation on the transport of dangerous goods.

As part of the evidence collected in the course of this project, in addition to technical evidence, feedback on the broader impacts of the proposed amendment was also received. While the scope of this work is focussed on the technical analysis of waste streams and their hazard classification based on their material composition, the proposed classification also has operational impacts on waste handling.

It is important to note that most stakeholders expressed concern over the broader implications of reclassification of waste streams as hazardous. Some of the main predictable impacts are summarised below.

Table 34. Potential impact of classification of waste as hazardous

Waste type			Waste management operation	Main operators impacted	Example of operational impact	Potential solutions
Waste batt	Mfg waste	Interm wastes				
√			Collection of waste batteries from households	Collection points [65], PROs, waste transport operators	- Accumulation of large amounts of batteries (potential hazard) while awaiting collection by a licensed operator	Derogation for small operators e.g. ADR, Special Provision 636
√			Transport of waste batteries	Waste transport operators	- Licencing of transport operators (ADR + hazardous waste certified lorry drivers) and associated costs	Inter-MS coordination to facilitate Prior Informed Consent procedure and similar for waste shipments
√			Storage of waste batteries	Collection points, waste storage facilities	- Licencing / permitting of storage facility for handling new waste codes - Accumulation of large amounts of batteries (potential hazard) while awaiting collection by a licensed operator	Derogation for small operators e.g. ADR, Special Provision 636
	√		Storage and transport of manufacturing waste	Battery manufacturers, waste transport operators	- Licencing / permitting of storage facility for handling new waste codes - Licencing of transport operators (ADR + hazardous waste certified lorry drivers) and associated costs	Accelerated national procedures for issuing permits
√	√	√	Processing of waste batteries (treatment and recycling)	Recyclers, waste transport operators	- Licencing / permitting of waste handlers for new waste codes	
		√	Transport of intermediate wastes e.g. black mass	Waste transport operators	- Licencing of transport operators (ADR + hazardous waste certified lorry drivers) and associated costs	- Inter-MS coordination to facilitate Prior Informed Consent procedure and similar for waste shipments

[65] e.g. supermarkets and other retailers such as e-bike shops, DIY shops, but also schools and offices

4.4.3. Other impacts of waste classification

Regardless of the hazard classification analysed in more detail above, the greater number of waste codes proposed will entail additional administrative burden for the operators involved in the classification of the waste. In addition, taking into account the new waste codes will require new permits and licensing or modification of existing ones, subject to administrative approval.

It is therefore anticipated that an adaptation period facilitating the entry into force of the new waste codes will be necessary and should be coordinated at EU level and facilitated through national measures.

5. Recommendations for the targeted amendment of the LoW entries

5.1. Battery manufacturing waste

Table 35. Recommendation for the adaption of the LoW regarding batteries manufacturing waste. New entries or new wording are highlighted in red.

16	**Waste not otherwise specified in the list**		
16 06	~~**Batteries and accumulators**~~	**Wastes from the manufacture, supply and use of batteries**	
Current LoW entries		**Proposal for LoW amendment**	
		16 06 21*	Lead-acid battery manufacturing waste containing hazardous substances (for example lead paste, lead scrap)
		16 06 22	Lead-acid battery manufacturing waste other than those mentioned in 16 06 21
		16 06 23*	Lithium-based battery manufacturing waste containing hazardous substances (for example including cathode cut-offs, waste, cathode slurry)
		16 06 24	Lithium-based battery manufacturing waste other than those mentioned in 16 06 23 (for example including anode cut-offs)
		16 06 25*	Nickel-based battery manufacturing waste containing hazardous substances (for example waste streams containing liquid and solid cathode material)
		16 06 26	Nickel-based battery manufacturing waste other than those mentioned in 16 06 25
		16 06 27*	Alkaline-based battery manufacturing waste containing hazardous substances
		16 06 28	Alkaline-based battery manufacturing waste other than those mentioned in 16 06 27
		16 06 29*	Zinc-based battery manufacturing waste containing hazardous substances
		16 06 30	Zinc-based battery manufacturing waste other than those mentioned in 16 06 29
		16 06 31*	Sodium-based battery manufacturing waste containing hazardous substances
		16 06 32	Sodium-based battery manufacturing waste other than those mentioned in 16 06 31
		16 06 33*	Battery manufacturing waste containing hazardous substances other than those mentioned in 16 06 21, 16 06 23, 16 06 25, 16 06 27, 16 06 29 and 16 06 31
		16 06 34	Battery manufacturing waste other than those mentioned in 16 06 22, 16 06 24, 16 06 26, 16 06 28, 16 06 30 and 16 06 32

5.2. Waste batteries

Table 36. Recommendation for the adaption of the LoW regarding waste batteries. New entries or new wording are highlighted in red.

16	**Waste not otherwise specified in the list**		
16 06	**~~Batteries and accumulators~~ Wastes from the manufacture, supply and use of batteries**		
Current LoW entries		**Proposal for LoW amendment**	
16 06 01*	Lead batteries	16 06 01*	Waste lead-acid batteries
16 06 02*	Ni-Cd batteries	16 06 02*	Waste nickel-cadmium batteries-
16 06 03*	Mercury-containing batteries	16 06 03*	Waste mercury-containing batteries
16 06 04	Alkaline batteries (except 16 06 03)	16 06 04*	Waste alkaline-based batteries (except 16 06 03)
16 06 05	Other batteries and accumulators	16 06 05	Waste batteries not otherwise specified other than those mentioned in 16 06 07
16 06 06*	Separately collected electrolyte from batteries and accumulators	16 06 06*	Separately collected electrolyte from waste batteries ~~and accumulators~~
		16 06 07*	Waste batteries not otherwise specified containing hazardous substances
		16 06 08*	Waste lithium-based batteries
		16 06 09*	Waste nickel-based batteries other than those mentioned in 16 06 02 (e.g. NiMH, Na-$NiCl_2$)
		16 06 10*	Waste zinc-based batteries, including silver oxide batteries
		16 06 11*	Waste sodium-based batteries containing hazardous substances (except 16 06 13)
		16 06 12	Other waste sodium-based batteries
		16 06 13*	Waste sodium sulphur batteries
		16 06 14*	Unsorted waste batteries
20	**Municipal wastes (household waste and similar commercial, industrial and institutional waste) including separately collected fractions**		
20 01	**Separately collected fractions (except 15 01)**		
20 01 33*	Batteries and accumulators included in 16 06 01, 16 06 02 or 16 06 03 and unsorted batteries and accumulators containing these batteries	20 01 33*	Waste batteries ~~and accumulators~~ included in categories 16 06 01~~, 16 06 02 or 16 06 03~~ to 16 06 04, 16 06 07 to 16 06 11, 16 06 13 and unsorted waste batteries ~~and accumulators~~ containing those waste batteries
20 01 34	Batteries and accumulators other than those mentioned in 20 01 33	20 01 34	Waste batteries ~~and accumulators~~ other than those mentioned in 20 01 33

5.3. Intermediate fractions from waste battery recycling

Table 37. Recommendation for the adaption of the LoW regarding intermediate fractions from waste battery recycling

19	**Wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use**		
19 02	**Wastes from physico/chemical treatments of waste (including dechromatation, decyanidation, neutralisation)**		
Current LoW entries		**Recommendation for LoW amendment**	
		19 02 12*	Solid salts and solutions containing heavy metals from battery recycling
10	**Wastes from thermal processes**		
10 04	**Wastes from lead thermal metallurgy**		
10 04 01	slags from primary and secondary production		
10 08	**Wastes from other non-ferrous thermal metallurgy**		
		10 08 21*	Slags from waste lithium-based battery recycling containing hazardous substances
		10 08 22	Slags from waste lithium-based battery recycling other than those mentioned in 10 08 21
		10 08 23*	Slags from waste nickel-based battery recycling containing hazardous substances
		10 08 24	Slags from waste nickel-based battery recycling other than those mentioned in 10 08 23
		10 08 25*	Slags from other waste battery recycling containing hazardous substances except 10 04 01
		10 08 26	Slags from other waste battery recycling other than those mentioned in 10 08 25
19	**Waste from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use**		
19 14	**Wastes from the mechanical / thermal treatment of waste batteries**		
		19 12 01*	Intermediate fraction from the thermal/mechanical treatment of waste lead-acid batteries and lead-acid battery manufacturing waste containing a mixture of electrode materials
		19 12 02*	Intermediate fraction from the thermal/mechanical treatment of waste lithium-based batteries and lithium-based battery manufacturing waste containing a mixture of electrode materials
		19 12 03*	Intermediate fraction from the thermal/mechanical treatment of waste nickel-based batteries and nickel-based battery manufacturing waste containing a mixture of electrode materials
		19 12 04*	Intermediate fraction from the thermal/mechanical treatment of waste alkaline-based batteries and alkaline-based battery manufacturing waste containing a mixture of electrode materials
		19 12 05*	Intermediate fraction from the thermal/mechanical treatment of waste zinc-based batteries and zinc-based battery manufacturing waste containing a mixture of electrode materials

		19 12 06*	Intermediate fraction from the thermal/mechanical treatment of waste sodium-based batteries and sodium-based battery manufacturing waste containing a mixture of electrode materials
		19 12 07*	Intermediate fraction from the thermal/mechanical treatment of waste batteries and battery manufacturing waste containing a mixture of electrode materials, not otherwise specified in 19 12 13 to 19 12 18
		19 12 08	Alloys from waste battery recycling [in massive form]

6. Conclusion and way forward

Currently, the List of Waste entries relevant to batteries contain only a handful of waste codes which do not always accurately represent commercially relevant chemistries or other fractions in the battery value chain.

Based on research by the JRC, we recommend potential new entries in the European List of Waste to better reflect the reality of the wastes associated to batteries. In particular, we recommend extending the list of battery types considered to include not only lead, nickel-cadmium, mercury and alkaline, but also lithium, (other) nickel, zinc, and sodium chemistries explicitly.

In addition, in many cases we recommend adding codes in the relevant sections of the List of Waste to capture not only waste batteries, but also battery manufacturing wastes, and intermediate fractions in the processing of battery-related waste. Following in-depth analysis of the available evidence for current and future compositions of these wastes, and also taking into account the variability in composition, recommended waste codes are categorised as hazardous or non-hazardous (or mirror entries).

A potential amendment of the list of waste taking these recommendations into account would help better capture and monitor the reality of waste handling in the value chains related to batteries, leading to better functioning markets, increased safety and improved environmental impacts.

References

Abbas, Q., Mirzaeian, M., Olabi, A.G., Gibson, D., 2021. Solid State Electrolytes. Encycl. Smart Mater. 4, 382–392. https://doi.org/10.1016/B978-0-12-803581-8.11740-0

Abraham, K.M., 2020. How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts? ACS Energy Lett. 5, 3544–3547. https://doi.org/10.1021/acsenergylett.0c02181

Accurec, 2023. Recycling of Nickel-Metal Hydrid Batteries. Access on 6.11.2023.

Al-Thyabat, S., Nakamura, T., Shibata, E., Iizuka, A., 2013. Adaptation of minerals processing operations for lithium-ion (LiBs) and nickel metal hydride (NiMH) batteries recycling: Critical review. Miner. Eng. 45, 4–17. https://doi.org/10.1016/j.mineng.2012.12.005

Armand, M., Ortiz-vitoriano, N., Olarte, J., Salazar, A., Ferret, R., 2023. Salt Batteries : Opportunities and applications of storage systems based on sodium nickel chloride batteries.

Arnberger, A., Höhns, H., 2023. Classification Battery streams. Saubermacher/REDUX Battery recycling. March 2023.

ASYS, 2022. ASYS - The waste monitoring system of the state authorities. Saxon State Ministry for Energy, Climate Protection, Environment and Agriculture [WWW Document]. URL https://www.wertstoffe.sachsen.de/asys-das-abfalluberwachungssystem-der-landerbehorden-26441.html

Avicenne Energy, 2023. The rechargeable battery market and main trends 2022-2030. ICBR 2023, Valencia.

Ballantyne, A.D., Hallett, J.P., Jason, D., Shah, N., Payne, D.J., Payne, D.J., 2018. Lead acid battery recycling for the twenty-first century Subject Category. R. Soc. Open Sci. 5. https://doi.org/http://dx.doi.org/10.1098/rsos.171368

Batrec, 2023. Batrec - Swiss quality recycling solution.

Batzer, M., Gundlach, D., Michalowski, P., Kwade, A., 2023. Scalable Production of Separator and Cathode Suspensions via Extrusion for Sulfidic Solid-State Batteries. ChemElectroChem 10. https://doi.org/10.1002/celc.202300452

BOE, 2021. Boletin oficial del estado. numero 17. 796. Real Decreto 27/2021, de 19 de enero, por el que se modifican el Real Decreto 106/2008, de 1 de febrero, sobre pilas y acumuladores y la gestión ambiental de sus residuos, y el Real Decreto 110/2015, de 20 de fe.

Böhm, H., Beyermann, G., 1999. ZEBRA batteries, enhanced power by doping. J. Power Sources 84, 270–274. https://doi.org/https://doi.org/10.1016/S0378-7753(99)00327-4

Brückner, L., Frank, J., Elwert, T., 2020. Industrial Recycling of Lithium-Ion Batteries — A Critical Review of Metallurgical Process Routes. Metals (Basel). 10, 1107.

Buqa, H., Carpentier, C., 2024. PFAS alternatives for batteries. Leclanche. Energy Storage Solution. Seminar on Alternatives to PFAS. EU Workshop in Brussels. 30.1.2024.

Dadé, M., Wallmach, T., Laugier, O., 2022. Detailed Microparticle Analyses Providing Process Relevant Chemical and Microtextural Insights into the Black Mass. Minerals 12. https://doi.org/10.3390/min12020119

Das, D., Manna, S., Puravankara, S., 2023. Electrolytes, Additives and Binders for NMC Cathodes in Li-Ion Batteries—A Review. Batteries 9. https://doi.org/10.3390/batteries9040193

Donnelly, L., Pirrie, D., Power, M., Corfe, I., Kuva, J., Lukkari, S., Lahaye, Y., Liu, X., Butcher, A., 2022. The sampling and phase characterisation of black mass, in: Proceedings of WCSB10: TOS Forum. pp. 397–409. https://doi.org/10.1255/tosf.166

EASE, 2016. Sodium-Nickel chloride Battery. Electrochemical Energy Storage. European Association for Storage of Energy (EASE).

Ebin, B., Petranikova, M., Ekberg, C., 2018. Physical separation, mechanical enrichment and recycling-oriented characterization of spent NiMH batteries. J. Mater. Cycles Waste Manag. 20, 2018–2027. https://doi.org/10.1007/s10163-018-0751-4

EC, 2018. Notices from European Union Institutions, bodies, offices and agencies. Commission notice on technical guidance on the classification of waste (2018/C 124/01).

EC, 2000. Commission Decision of 3 May 2020 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of.

ECHA, 2023. Database on classification and labelling information on notified and registered substances received from manufacturers and importers. European Chemicals Agency.

EDI, 2023. Written input to the JRC stakeholder consultation. Euro Dieuze Industrie (EDI, Veolia's Group).

EDM, 2022. Electronic Data Management - Environment (EDM) Specified waste types according to the Austrian "Abfallverzeichnisverordnung" (Waste Catalogue Ordinance) [WWW Document]. URL https://secure.umweltbundesamt.at/edm_portal/home.do

Elwert, T., Strauss, K., Thomas, S., Goldmann, D., 2012. Phase composition of high lithium slags from the recycling of lithium ion batteries. World Metall. - Erzmetall, GDMB - Medien. Clausthal-Zellerfeld, 65, 163–171.

Energizer Brands, 2018. Alkaline Manganese Dioxide Handbook and Application Manual 1–14.

Envirobat-Espana, 2023. Alkaline batterie recycling. Personal consultation of Borja Álvarez Muñoz (CEO Envirobat-Espana, 22.02.2023).

EPA (Ireland), 2019. Waste Classification - List of Waste & Determining if Waste is Hazardous or Non-hazardous. Environmental Protection Agency (Ireland).

EUROSTAT, 2023. Recycling of batteries and accumulators [WWW Document]. env_wasbat. https://doi.org/doi.org/10.2908/ENV_WASBAT

Fastmarkets, 2023. Battery recycling and black mass pricing. Presentation at ICBR 2023 (International Battery Recycling Congress)

FDK, 2024. Manufacturing process of FUJITSU batteries available at https://www.fdk.com/cyber-e/pi_bt_process.html.

Fraunhofer, 2022. Solid-State Battery Roadmap 2035 +. Fraunhofer Institute for Systems and Innovation Research ISI. Karlsruhe, April 2022 112.

FZSONICK, 2023. Written input to the JRC stakeholder consultation.

Gao, W., Yu, L., Lin, H., Meng, L., Yu, S., Li, J., Lin, Y., Zheng, Y., 2024. A review on the impacts of fluorinated organic additives in lithium battery industry—an emerging source of per-and polyfluoroalkyl substances. Crit. Rev. Environ. Sci. Technol. https://doi.org/https://doi.org/10.1080/10643389.2024.2306093

Holmberg, F., 2017. Recycling of nickel metal hydride (NiMH) batteries. Characterization and recovery of nickel, AB5 alloy and cobalt. Industrial Materials Recycling - Department of Chemistry and Chemical Engineering, Chalmers University of Technology, Gothenburg. Sweden.

HSE, 2024. Electric and hybrid vehicles- Risks of working with E&HVs. Health and Safety Executive (HSE). Access on 12.3.2024.

Huisman, J., Bobba, S., 2021. "Available for Collection" study on alternative collection targets for waste portable and light means of transport batteries. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/64633

IEA, 2023. Global EV Outlook 2023. Paris.

ILO, 2011. Lead-acid battery manufacture. ILO Encyclopaedia of Occupational Health & Safety, https://iloencyclopaedia.org/part-xiii-12343/electrical-appliances-and-equipment/item/661-lead-acid-battery-manufacture

INERIS, 2014. Déchets de batteries au lithium : classement et état des lieux des filières de gestion. INERIS-DRC-14-141681-06454A.

Jean-Fulcrand, A., Jeon, E.J., Karimpour, S., Garnweitner, G., 2023. Cross-Linked Solid Polymer-Based Catholyte for Solid-State Lithium-Sulfur Batteries. Batteries 9, 341. https://doi.org/10.3390/batteries9070341

Kellermann, G., Metz, K., 2023. Factsheet: PFAS in Batteries. ZVEI e.V. Electro and Digital Industry Association.

Kitajou, A., Yamashita, M., Kobayashi, W., Okada, M., Nanami, T., Muto, S., 2022. Anode Properties of NaTi2(PO4)3 Prepared by Adding Excess Na2CO3 for Aqueous Sodium-Ion Batteries. ACS Appl. Energy Mater. 5.

https://doi.org/https://doi.org/10.1021/acsaem.2c01212

Kliimaministeerium Estonia, 2007. Order No 49 of the Minister of the Environment of 02.07.2007. “Specified list of waste from problematic products”. Annex (in the wording of Regulation No 34 of the Minister of the Environment of 25.06.2020). [WWW Document]. URL https://www.riigiteataja.ee/aktilisa/1270/6202/0002/KKM25062020_m34_lisa.pdf#mixed16 06 05other batteries and accumulators: other batteries and accumulators 16 06 05 01 other batteries other than those mentioned in 16 06 03*, 16 06 04, 16 06 05 05 and 16

Kononova, N., Blömeke, S., Cerdas, F., Zellmer, S., 2023. Identification of target materials for recycling of solid-state batteries from environmental and economic perspective using information theory entropy. Procedia CIRP 116, 185–190. https://doi.org/10.1016/j.procir.2023.02.032

LaCoste, J.D., Zakutayev, A., Fei, L., 2021. A review on lithium phosphorus oxynitride. J. Phys. Chem. C 125, 3651–3667. https://doi.org/10.1021/acs.jpcc.0c10001

Latini, D., Vaccari, M., Lagnoni, M., Orefice, M., Mathieux, F., Huisman, J., Tognotti, L., Bertei, A., 2022. A comprehensive review and classification of unit operations with assessment of outputs quality in lithium-ion battery recycling. J. Power Sources 546, 231979. https://doi.org/10.1016/j.jpowsour.2022.231979

Li, Y., Lian, F., Ma, L., Liu, C., Yang, L., Sun, X., Chou, K., 2015. Fluoroethylene Carbonate as Electrolyte Additive for Improving the electrochemical performances of High-Capacity Li1.16[Mn0.75Ni0.25]0.84O2 Material. Electrochim. Acta 168, 261–270. https://doi.org/10.1016/j.electacta.2015.04.030

Liu, Y., Zhang, R., Wang, J., Wang, Y., 2021. Current and future lithium-ion battery manufacturing. iScience 24, 17. https://doi.org/10.1016/j.isci.2021.102332

Ma, Y., Svärd, M., Xiao, X., Gardner, J.M., Olsson, R.T., Forsberg, K., 2020. Precipitation and Crystallization Used in the Production of Metal Salts for Li-Ion Battery Materials : A Review.

Mazur, A., Penha, F.M., 2023. Recovery of Metals from Lithium Ion Battery Recycling through Simultaneous Precipitation of Hydroxide Metal Salts. International Symposium of Industrial Crystallization 2023 (ISIC). Glasgow, United Kingdom September, 5 - 8th , 2023.

McKinsey & Company, 2023. Battery recycling takes the driver’s seat [WWW Document].

Nikolic, M., B, N.S., Velenderic, M., Adjei, F., 2023. of Sodium-Nickel-Chloride Batteries. Atlantis Press International BV. https://doi.org/10.2991/978-94-6463-156-2

OCDE, 1995. Recycling of Copper , Lead and Zinc Bearing Wastes. Environment Monographs No 109. OCDE/GD(95)78. Organisation for economic co-operation and development. Development.

Ouyang, L., Huang, J., Wang, H., Liu, J., Zhu, M., 2017. Progress of hydrogen storage alloys for Ni-MH rechargeable power batteries in electric vehicles : A review. Mater. Chem. Phys. 200, 164–178. https://doi.org/10.1016/j.matchemphys.2017.07.002

Ravier, C., 2024. Personal information (06.02.2024). Direction Générale de la Prévention des Risques. Ministère de la transition écologique et de la cohésion des territoires.

RECHARGE, 2024. Written input to the JRC stakeholder consultation. RECHARGE.

RECHARGE, 2021. PFAS restriction proposal. RECHARGE statement for 2nd Call for Evidence – October 2021.

RECHARGE, 2023 (September). RECHARGE’s technical contribution for the ECHA PFAS Restriction Consultation. https://rechargebatteries.org/wp-content/uploads/2023/09/FINAL-SECOND-SUBMISSION-.pdf

Ren, G., Xiao, S., Xie, M., Pan, B., Fan, Y., Wang, F., Xia, X., 2016. Recovery of valuable metals from spent lithium-ion batteries by smelting reduction process based on MnO-SiO2-Al2O3 slag system. Advances in Molten Slags, Fluxes, and Salts: Proceedings of The 10th International Conference on Molten Slags, Fluxes and Salts. Appl. Mech. Mater. 97–103. https://doi.org/10.4028/www.scientific.net/AMM.440.97

REN, G. xing, XIAO, S. wen, XIE, M. qiu, PAN, B., CHEN, J., WANG, F. gang, XIA, X., 2017. Recovery of valuable metals from spent lithium ion batteries by smelting reduction process based on FeO–SiO2–Al2O3 slag system. Trans. Nonferrous Met. Soc. China (English Ed. 27, 450–456. https://doi.org/10.1016/S1003-6326(17)60051-7

Rensmo, A., Savvidou, E.K., Cousins, I.T., Hu, X., Schellenberger, S., Benskin, J.P., 2023. Lithium-ion battery recycling: a source of per- and polyfluoroalkyl substances (PFAS) to the environment? Environ. Sci. Process.

Impacts 25, 1015–1030. https://doi.org/10.1039/D2EM00511E

Si, R.J., Liu, D.Q., Xue, S.Q., 2018. Experimental Study on Fire and Explosion Suppression of Self-ignition of Lithium Ion Battery. Procedia Eng. 211, 629–634. https://doi.org/10.1016/j.proeng.2017.12.057

Siddiqi, S., Holland, A., 2023. Sodium-ion Batteries 2024-2034: Technology, Players, Markets, and Forecasts. IDTechEx Reseach.

Sobianowska-Turek, A., Urbańska, W., Janicka, A., Zawiślak, M., Matla, J., 2021. The necessity of recycling ofwaste li-ion batteries used in electric vehicles as objects posing a threat to human health and the environment. Recycling 6. https://doi.org/10.3390/recycling6020035

Spoerke, E.D., Gross, M.M., Percival, S.J., Small, L.J., 2021. Molten sodium batteries. Energy-Sustainable Adv. Mater. 59–84. https://doi.org/10.1007/978-3-030-57492-5_3

Sudworth, J.L., 2001. The sodium / nickel chloride (ZEBRA) battery 100.

Sun, R., You, Y., 2012. Prussian White Cathode Materials for All-Climate Sodium-Ion Batteries. ACS Appl. Mater. Interfaces 15, 44599–44606. https://doi.org/https://doi.org/10.1021/acsami.3c08521

Sundén, B., 2019. Battery technologies. Hydrog. Batter. Fuel Cells 57–79. https://doi.org/10.1016/b978-0-12-816950-6.00004-x

Tang, W., Song, X., Du, Y., Peng, C., Lin, M., Xi, S., Tian, B., Zheng, J., Wu, Y., Pan, F., Loh, K.P., 2016. High-performance NaFePO4 formed by aqueous ion-exchange and its mechanism for advanced sodium ion batteries. J. Mater. Chem. A.

TDRFORCE, 2023. How Alkaline Batteries Are Made: A Look into the Manufacturing Process [WWW Document].

Tracegrow, 2023. Using alkaline batteries safely as raw material for fertilizers.

Tracegrow, 2019. Method for processing black mass of spent alkaline batteries . Finish Patent and Registratio.

Trickett, D., 1998. Current status of health and safety issues of sodium/metal chloride (ZEBRA) batteries. NREL Publ. 1–53.

Umicore, 2016. Lithium-rich metallurgical slag. European Patent Office. EP 3 402 907 B1. Date of publication and mention of the grant of the patent: 09.03.2022.

Vanderbruggen, A., Gugala, E., Blannin, R., Bachmann, K., Serna-Guerrero, R., Rudolph, M., 2021. Automated mineralogy as a novel approach for the compositional and textural characterization of spent lithium-ion batteries. Miner. Eng. 169. https://doi.org/10.1016/j.mineng.2021.106924

VDMA, 2023. Roadmap Battery Production Equipment 2030. VDMA Battery Production. 1–63.

Wang, L., Li, J., Lu, G., Li, W., Tao, Q., Shi, C., Jin, H., Chen, G., Wang, S., 2020. Fundamentals of Electrolytes for Solid-State Batteries: Challenges and Perspectives. Front. Mater. 7, 1–5. https://doi.org/10.3389/fmats.2020.00111

Wang, S., Xie, Y., Guerrero, J.M., 2022. Market batteries and their characteristics, Nano Technology for Battery Recycling, Remanufacturing, and Reusing. Elsevier Inc. https://doi.org/10.1016/B978-0-323-91134-4.00010-8

Wang, Yanjie, Zhang, Y., Cheng, H., Ni, Z., Wang, Ying, Xia, G., Li, X., Zeng, X., 2021. Research progress toward room temperature sodium sulfur batteries: A review. Molecules 26. https://doi.org/10.3390/molecules26061535

Weber, C.J., Geiger, S., Falusi, S., Roth, M., 2014. Material review of Li ion battery separators. AIP Conf. Proc. 1597, 66–81. https://doi.org/10.1063/1.4878480

Windisch-Kern, S., Holzer, A., Ponak, C., Raupenstrauch, H., 2021. Pyrometallurgical lithium-ion-battery recycling: Approach to limiting lithium slagging with the indured reactor concept. Processes 9, 1–15. https://doi.org/10.3390/pr9010084

Wood Mackenzie, 2023. Sodium-ion update: A make-or-break year for the battery market disruptor.

Woodmac, 2023. Sodium-ion update: A make-or-break year for the battery market disruptor. Wood Mackenzie.

Wu, S., Kaden, N., Dröder, K., 2023. A Systematic Review on Lithium-Ion Battery Disassembly Processes for Efficient Recycling. Batteries 9, 297. https://doi.org/10.3390/batteries9060297

Yadav, P., Jie, C.J., Tan, S., Srinivasan, M., 2020. Recycling of cathode from spent lithium iron phosphate batteries. J. Hazard. Mater. 399, 123068. https://doi.org/10.1016/j.jhazmat.2020.123068

Yang, Z., Li, G., Sun, J., Xie, L., Jiang, Y., Huang, Y., Chen, S., 2019. High performance cathode material based on Na3V2(PO4)2F3 and Na3V2(PO4)3 for sodium-ion batterieso Title. Energy Storage Mater. 25. https://doi.org/10.1016/j.ensm.2019.09.014

Young, K.H., Cai, X., Chang, S., 2017. Reviews on Chinese patents regarding the Nickel/Metal hydride battery, Batteries. https://doi.org/10.3390/batteries3030024

Yu, D., Huang, Z., Makuza, B., Guo, X., Tian, Q., 2021. Pre-treatment options for the recycling of spent lithium-ion batteries : A comprehensive review. Miner. Eng. 173, 107218. https://doi.org/10.1016/j.mineng.2021.107218

Zackrisson, M., Schellenberger, S., 2020. Toxicity of lithium ion battery chemicals -overview with focus on recycling 1–21.

Zhang, G., Yuan, X., He, Y., Wang, H., Zhang, T., Xie, W., 2021. Recent advances in pretreating technology for recycling valuable metals from spent lithium-ion batteries. J. Hazard. Mater. 406, 124332. https://doi.org/10.1016/j.jhazmat.2020.124332

Zhang, L., Revathi, S., 2016. Batteries, Rechargeable. Ref. Modul. Mater. Sci. Mater. Eng. https://doi.org/doi:10.1016/B978-0-12-803581-8.01720-3

Zhao, Y., Kang, Y., Wozny, J., Lu, J., Du, H., Li, C., Li, T., Kang, F., Tavajohi, N., Li, B., 2023. Recycling of sodium-ion batteries. Nat. Rev. Mater. 8, 623–634. https://doi.org/10.1038/s41578-023-00574-w

Glossary and legal references

Glossary

Alloy: An alloy is a mixture of two or more metals, but can also be formed from combinations of metals and other elements.

Battery: means any device delivering electrical energy generated by direct conversion of chemical energy, having internal or external storage, and consisting of one or more non-rechargeable or rechargeable battery cells, modules or of packs of them, and includes a battery that has been subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing (according to EU 2023/1542).

Battery cell: means the basic functional unit in a battery, composed of electrodes, electrolyte, container, terminals and, if applicable, separators, and containing the active materials the reaction of which generates electrical energy (according to EU 2023/1542).

Battery module: means any set of battery cells that are connected together or encapsulated within an outer casing to protect the cells against external impact, and which is meant to be used either alone or in combination with other modules (according to EU 2023/1542)

Battery pack: means any set of battery cells or modules that are connected together or encapsulated within an outer casing, to form a complete unit which is not meant to be split up or opened by the end-user (according to EU 2023/1542)

Black mass: is the fine grained powder-like material output originating from waste batteries and/or battery manufacturing waste after a cascade of different mechanical and/or also thermal treatment steps. Black mass contains the valuable metals and also graphite that are part of the cathode and anode, but also the electrolyte of the input material.

Hydrometallurgical recycling: refers to a process of extracting and recovering metals from various waste materials using aqueous solutions or solvents. This method involves dissolving the metal-containing materials in a (acid) liquid, followed by various chemical and physical processes to separate and purify the metals from the solution.

Lithium-based batteries: The term encompasses different categories of lithium-based batteries, including lithium-ion batteries, rechargeable (secondary) batteries that use lithium ions as the charge carrier, and lithium-metal batteries (primary or secondary), that use lithium metal at the anode.

Mechanical recycling: consists of various treatment steps such as crushing and shredding, drying, sieving, sorting) without significantly changing the material's chemical structure.

Thermal recycling: A thermal treatment step (e.g. pyrolysis) can be applied at different points of the mechanical recycling to remove plastics, rubber, paper, electrolyte and potentially hazardous fluorine-containing components. The temperature uses does not smelt the material, compared to pyrometallurgical recycling.

Nickel-based batteries: The term encompasses different categories of nickel-based batteries, including nickel-metal-hydrate and sodium-nickel-chloride batteries.

Precipitated metal salts: The treatment of black mass with acids and subsequent precipitation can result in mixed metal salts (as e.g. hydroxide precipitate), that contains the metals from the black mass in a different chemical form. This material is still considered as an intermediate in the battery recycling process.

Pyrometallurgical recycling: is a process of recycling metals and other materials by using high temperatures to melt and separate components. This method involves heating the materials to high temperatures in a furnace, where the metals melt and can be separated from other components

Slag: is a by-product formed during the smelting, refining, or manufacturing of metals and other materials. It consists of the non-metallic components, including impurities, oxides, and other compounds that are separated and removed during the processing of ores and metals.

Waste battery (according to EU 2023/1542): any battery which is waste as defined in Article 3, point (1), of Directive 2008/98/EC

Legal references and acronyms

Table 38. Legal references and acronyms

Acronym	Meaning	Reference
ADR	Accord relatif au transport international des marchandises Dangereuses par Route (Agreement concerning the international carriage of Dangerous goods by Road)	https://unece.org/transport/standards/transport/dangerous-goods/adr-2023-agreement-concerning-international-carriage
BWBR	Batteries and waste batteries Regulation	Regulation (EU) 2023/1542
CLP	Classification, Labelling and Packaging Regulation	Regulation EC 1272/2008
GHS	Globally Harmonized System of Classification and Labelling of Chemicals	https://unece.org/about-ghs
LoW	List of Waste	Commission Decision 2000/532/EC
POP	Regulation on persistent organic pollutants	Regulation (EC) No 850/2004
REACH	Regulation on the registration, evaluation, authorisation and restriction of chemicals	Regulation (EC) 1907/2006
TGCW	Technical guidance on the classification of waste	Commission notice 2018/C 124/01
WFD	Waste Framework Directive	Directive 2008/98/EC
WSR	Waste Shipment Regulation	Regulation (EC) 1013/20060

List of other abbreviations and definitions

°C	Degree Celsius
Ag-O	Silver Oxide
Ag-Zn	Silver Zinc
AH	Absolute hazardous (LoW entry)
ANH	Absolute non-hazardous (LoW entry)
BDEs	Brominated diphenyl ethers
BM	Black mass
BMS	Battery Management Systems
CAS No	Chemical Abstracts Service registry number
C&L	Classification and Labelling
ECHA	European Chemical Agency
ELV	End-of-Life Vehicle
GWh	Gigawatt hours
HCBD	Hexachlorobutadiene
HP	Hazardous properties
JRC	Joint Research Centre
kt	kilotonne
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LiSOCl	Lithium Thionyl Chloride
LMO	Lithium Manganese Oxide
LMT	Light means of transport
LTO	Lithium Titanium Oxide
MH	Mirror hazardous (LoW entry)
MNH	Mirror non-hazardous (LoW entry)
MnO	Manganese Oxide
MnO_2	Manganese Dioxide
MFSU	Wastes from the Manufacture, Formulation, Supply and Use
NaAlCl	Sodium Aluminium Chloride
NaCl	Sodium Chloride
NCA	Lithium Nickel Cobalt Aluminium
$Na\text{-}NiCl_2$	Sodium Nickel Chloride
$NiCl_2$	Nickel chloride
NiMH	Nickel Metal Hydrate
NMC	Nickel Manganese Cobalt
PFOS	Perfluorooctane sulfonates
SIB	Sodium-Ion Battery

SBR	Styrene Butadiene Rubber
SCCP	Short-chain chlorinated paraffins
SDS	Safety Data Sheet
TDG	UN framework for the Transport of Dangerous Goods
WEEE	Waste from Electrical and Electronic Equipment
Zn-air	Zinc air
Zn-C	Zinc carbon
Zn-Cl	Zinc chloride

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Annex 1. Properties of waste which render it hazardous (description taken from WFD, Annex III[66])

Table 39. Hazardous properties according to the WFD Annex III

Hazardous Properties	
HP1	Explosive
HP2	Oxidising
HP3	Flammable
HP4	Irritant — skin irritation and eye damage
HP5	Specific Target Organ Toxicity (STOT)/Aspiration Toxicity
HP6	Acute Toxicity
HP7	Carcinogenic
HP8	Corrosive
HP9	Infectious
HP10	Toxic for reproduction
HP11	Mutagenic
HP12	Release of an acute toxic gas
HP13	Sensitising
HP14	Ecotoxic
HP15	Waste capable of exhibiting a hazardous property listed above not directly displayed by the original waste

[66] as amended by Commission Regulation (EU) No 1357/2014 of 18 December 2014 replacing Annex III to Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directives Text with EEA relevance

Annex 2. **List of substances in Annex IV of the POP regulation**

Table 40. List of substances (Annex IV) subject to waste management provisions set out in Article 7 of the POP Regulation

Substance	**CAS No**	**EC No**	**Concentration limit referred to in Article 7(4)(a)**
Endosulfan	115-29-7 959-98-8 33213-65-9	204-079-4	50 mg/kg
Hexachlorobutadiene	87-68-3	201-765-5	100 mg/kg
Polychlorinated naphthalenes			10 mg/kg
Alkanes C_{10}-C_{13}, chloro (short-chain chlorinated paraffins) (SCCPs)	85535-84-8	287-476-5	1 500 mg/kg The Commission shall review that concentration limit and shall, where appropriate, adopt a legislative proposal to lower that value no later than 30 December 2027
Tetrabromodiphenyl ether $C_{12}H_6Br_4O$	40088-47-9 and others	254-787-2 and others	Sum of the concentrations of tetrabromodiphenyl ether $C_{12}H_6Br_4O$, pentabromodiphenyl ether $C_{12}H_5Br_5O$, hexabromodiphenyl ether $C_{12}H_4Br_6O$, heptabromodiphenyl ether $C_{12}H_3Br_7O$ and decabromodiphenyl ether $C_{12}Br_{10}O$: (a) until 29 December 2027, 500 mg/kg; (b) from 30 December 2025 until 28 December 2027, 350 mg/kg, or, if higher, the sum of the concentration of those substances where they are present in mixtures or articles, as set out in the fourth column, point 2, of Annex I for the substances tetrabromodiphenyl ether, pen tabromodiphenyl ether, hexabromodiphenyl ether, heptabromodiphenyl ether and decabromodiphenyl ether; c) from 30 December 2027, 200 mg/kg or, if higher, the sum of the concentration of those substances where they are present in mixtures or articles, as set out in the fourth column, point 2, of Annex I for the sub stances tetrabromodiphenyl ether, pentabromodiphenyl ether, hexabromodiphenyl ether, heptabromodiphenyl ether and decabromodiphenyl ether.
Pentabromodiphenyl ether $C_{12}H_5Br_5O$	32534-81-9 and others	251-084-2 and others	
Hexabromodiphenyl ether $C_{12}H_4Br_6O$	36483-60-0 and others	253-058-6 and others	
Heptabromodiphenyl ether $C_{12}H_3Br_7O$	68928-80-3 and others	273-031-2 and others	
Decabromodiphenyl ether $C_{12}Br_{10}O$	1163-19-5 and others	214-604-9 and others	
Perfluorooctane sulfonic acid and its derivatives (PFOS) C8F17SO2X (X = OH, Metal salt (O-M+), halide, amide, and other derivatives including polymers)	1763-23-1 2795-39-3 29457-72-5 29081-56-9 70225-14-8 56773-42-3 251099-16-8 4151-50-2 31506-32-8 1691-99-2 24448-09-7 307-35-7 and others	217-179-8 220-527-1 249-644-6 249-415-0 274-460-8 260-375-3 223-980-3 250-665-8 216-887-4 246-262-1 206-200-6 and others	50 mg/kg
Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF) and dioxin-like polychlorinated biphenyls (dl-PCBs)			5 μg/kg[18] The Commission shall review that concentration limit and shall, where appropriate, adopt a legislative proposal to lower that value, where such lowering is feasible in accordance with scientific and technical progress, no later than 30 December 2027.
DDT (1,1,1-trichloro-2,2-bis (4-chlorophenyl)ethane)	50-29-3	200-024-3	50 mg/kg
Chlordane	57-74-9	200-349-0	50 mg/kg
Hexachlorocyclohexanes, including lindane	58-89-9 319-84-6 319-85-7 608-73-1	210-168-9 200-401-2 206-270-8 206-271-3	50 mg/kg
Dieldrin	60-57-1	200-484-5	50 mg/kg
Endrin	72-20-8	200-775-7	50 mg/kg
Heptachlor	76-44-8	200-962-3	50 mg/kg
Hexachlorobenzene	118-74-1	204-273-9	50 mg/kg

Chlordecone	143-50-0	205-601-3	50 mg/kg
Aldrin	309-00-2	206-215-8	50 mg/kg
Pentachlorobenzene	608-93-5	210-172-0	50 mg/kg
Polychlorinated Biphenyls (PCB)	1336-36-3 and others	215-648-1	50 mg/kg
Mirex	2385-85-5	219-196-6	50 mg/kg
Toxaphene	8001-35-2	232-283-3	50 mg/kg
Hexabromobiphenyl	36355-01-8	252-994-2	50 mg/kg
Hexabromocyclododecane[19]	25637-99-4, 3194-55-6, 134237-50-6, 134237-51-7, 134237-52-8	247-148-4221-695-9	500 mg/kg The Commission shall review that concentration limit and shall, where appropriate, adopt a legislative proposal to lower that value to not higher than 200 mg/kg no later than 30 December 2027.
Pentachlorophenol, its salts and esters	87-86-5 and others	201-778-6 and others	100 mg/kg
Dicofol	115-32-2	204-082-0	50 mg/kg
Perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds, as set out in Annex I	335-67-1 and others	335-67-1 and others	1 mg/kg (PFOA and its salts), 40 mg/kg (sum of PFOA-related compounds) The Commission shall review that concentration limit and shall, where appropriate, adopt a legislative proposal to lower that value, where such lowering is feasible in accordance with scientific and technical progress, no later than 30 December 2027.
Perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS- related compounds	355-46-4 and others	355-46-4 and others	1 mg/kg (PFHxS and its salts), 40 mg/kg (sum of PFHxS-related compounds). The Commission shall review that concentration limit and shall, where appropriate, adopt a legislative proposal to lower that value, where such lowering is feasible in accordance with scientific and technical progress, no later than 30 December 2027.

Annex 3. Sodium-nickel chloride battery manufacturing waste

Table 41. Waste codes assigned to waste streams from sodium-nickel chloride battery manufacturing

Na-$NiCl_2$ battery manufacturing waste streams (path of the waste stream)	Material	Assigned waste codes
All the flow (recycling)	Iron	16 01 17
All the flow (recycling) – ferrous metal	Stainless steel	16 01 17
Ceramic electrolyte production (recycling)	Ceramic	06 03 99
Batteries assembly (disposal)	Insulation	16 11 06
BMS[67] production (recycling)	Electronic waste	16 01 18
Batteries assembly (recycling)	Copper	16 03 04
Cathode material production (recycling)	Nickel	16 01 18
Batteries assembly (disposal)	Mica	01 04 99
Production of liquid cathode material (disposal)	Melt Salts	16 03 03*
Production of solid cathode material, cells assembly (recycling)	Nickel granulate	16 03 03*
Cells and batteries assembly waste (recycling)	Batteries/Cells Sodium Nickel	16 06 05
All the flow (disposal)	Sludge	19 08 13*

[67] Battery management system (BMS)

Annex 4. Background information on the composition of lithium-based batteries

Table 42. Background information on the composition of different lithium battery chemistries including the weight (percent) distribution

Battery component	Chemistries of lithium-based batteries and materials										
	LCO	**LMO**	**NMC**	**NCA**	**% total battery**	**LTO**	**% total battery**	**LFP**	**% total battery**	**LiSOCl**	**% total battery**
Cathode material	$LiCoO_2$	$Li_xMn_yO_4$	$LiNi_xMn_yCo_zO_2$	$LiNi_xCo_yAl_zO_2$	20–50 %	$LiMO_2$	20–50 %	$LiFePO_4$	25–50 %	$SOCl_2$ $AlCl_3$	18–45 % 1–5 %
Cathode current collector	Aluminium foil				8–15 %	Aluminium foil	6–8 %	Aluminium foil	6–8 %	Aluminium foil	no data
Anode material	Graphite SiO_2 (Silicon dioxide) Carbon black				10–30 % no data 1–3 %	$Li_4Ti_5O_{12}$ (lithium-titanate nanocrystals)	unknown	Graphite	10–30 %	Graphite	2–5 %
Anode current collector	Copper foil				4–7 %	Copper foil	10–12 %	Copper foil	10–12 %	Copper foil	no data
Electrolyte	**Lithium salts**				10–20 %	**Lithium salts**	10–20 %	**Lithium salts**	10–20 %	Li–metal	2–6 %
	$LiPF_6$ (Lithium Hexafluorophosphate)					$LiPF_6$		$LiPF_6$		$LiGaCl_4$	0–2 %
	$LiBF_4$ (Lithium Tetrafluoroborate)					$LiBF_4$		$LiBF_4$		LiCle	1–2 %
	$LiClO_4$ (Lithium Perchlorate)					LiFSI		LiFSI			
	Organic solvents					**Organic solvents**		**Organic solvents**			
	$C_3H_4O_3$ (Ethylene carbonate)					$C_3H_4O_3$		$C_3H_4O_3$			
	$C_4H_6O_3$ (Propylene carbonate)					$C_4H_6O_3$		$C_4H_6O_3$			
	$(CH_3O)_2CO$ (Dimethyl carbonate)					$(CH_3O)_2CO)$		$(CH_3O)_2CO)$			
	$C_3H_2O_3$ (Vinylene Carbonate)					$C_3H_2O_3$		$C_3H_2O_3$			
	C_6H_5F (Fluorobenzene)					C_6H_5F		C_6H_5F			
	LiF_2PO_2 (Lithium difluorophosphate)					LiF_2PO_2		LiF_2PO_2			
	$F_2LiNO_4S_2$ (Lithium bis(fluorosulfonyl)imide)					$F_2LiNO_4S_2$		$F_2LiNO_4S_2$			
	$C_3H_6O_3S$ (1,3-Propanesultone)					$C_3H_6O_3S$		$C_3H_6O_3S$			
	$C_8H_{12}Si$ (Tetravinylsilane)					$C_8H_{12}Si$		$C_8H_{12}Si$			
	$C_2H_4O_4S$ (1,3,2-Dioxathiolane 2,2-dioxide)					$C_2H_4O_4S$		$C_2H_4O_4S$			
	$LiCF_3SO_3$ (Lithium trifluoromethanesulfonate (Li-Triflate)					$LiCF_3SO_3$		$LiCF_3SO_3$			
	$LiC_2F_6NO_4S_2$ (Lithium bis(trifluoromethanesulfonyl)imide)					$LiC_2F_6NO_4S_2$		$LiC_2F_6NO_4S_2$			
	$C_4F_{10}LiNO_4S_2$ (Lithium bis(pentafluoroethanesulfonyl)imide					$C_4F_{10}LiNO_4S_2$		$C_4F_{10}LiNO_4S_2$			
	$C_6F_3LiN_4$ (Lithium 4,5-dicyano-2-(trifluoromethyl)imidazol-1-ide)					$C_6F_3LiN_4$		$C_6F_3LiN_4$			
	$C_6H_5CF_3$ (Trifluorotoluene)					$C_6H_5CF_3$		$C_6H_5CF_3$			
	$C_6H_6BF_9O_3$ (Tris(2,2,2-trifluoroethyl)borate)					$C_6H_6BF_9O_3$		$C_6H_6BF_9O_3$			
	$(C_2H_5O)_2CO$ (Diethyl Carbonate)					$(C_2H_5O)_2CO$		$(C_2H_5O)_2CO$			
	$C_4H_8O_3$ (Ethyl methyl carbonate)					$C_4H_8O_3$		$C_4H_8O_3$			
	$C_4H_8O_2$ (Ethyl Acetate)					$C_4H_8O_2$		$C_4H_8O_2$			

Binder	PVDF (polyvinylidene fluoride) dissolved in N-methyl-2-pyrrolidone (NMP) PTFE (Polytetrafluoroethylene) in unknown solvent CMC (Carboxy methyl cellulose) in aqueous solvent Na-alginate in aqueous solvent LA132 (Polyacrylic latex) in aqueous solvent PPA (Poly(acrylic acid)) in aqueous solvent PDADMA (Poly(diallyldimethylammonium) in aqueous solvent Carbon black	1–8 %	PVDF PTFE CMC Na-alginate LA132 PPA PDADMA Carbon black	1–8 %	PVDF CMC	0.30 % 0.30 %	PTFE	0–1 %
Separator	Polymeric membranes (e.g. PE or PP) Non-woven fabric mats Styrene Butadiene Rubber (SBR)	3–5 %	Polymeric membranes Non-woven fabric mats	3–5 %	Polyethylene Nylon Styrene Butadiene Rubber (SBR)	3–4 % 4 % 0.05 %	Polymeric membranes	3–5 %
Case and tab	Steel, plastic	15–30 %	Steel, plastic	15–30 %	Steel, plastic	25–30 %	Steel, plastic	15–30 %

Annex 5. Chemical compounds in Li-$SOCl_2$ batteries

Table 43. Chemical compounds in Li-$SOCl_2$ batteries with hazard identification according to CLP (1272/2008)

Chemical compound	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
$SOCl_2$	18–47 % (30–45 %)	7719-09-7	Harmonised C&L	H302	Acute Tox. 4	≥ 25 %	°Y	HP6
				H314	Skin Corr. 1A	≥ 5 %	Y	HP8
				H332	Acute Tox. 4	≥ 22,5 %	°Y	HP6
SO_2Cl_2	30–45 %	7791-25-5	Harmonised C&L	H314	Skin Corr. 1B	≥ 25 %	°Y	HP6
				H335	STOT SE 3	≥ 20 %	°Y	HP5
$AlCl_3$	1–5 %	7446-70-0	Harmonised C&L	H314	Skin Corr. 1B	≥ 5 %	°N	HP8
Carbon black	2–6 %	1333-86-4	REACH registration C&L	-	-	-	-	-
LiMe	2–6 %	7439-93-2	Harmonised C&L	H260	Water-react. 1	0.1 %	Y	HP3
				H314	Skin Corr. 1B	≥ 5 %	°Y	HP8
$GaCl_4$	0–2 %	13450-90-3	REACH registration C&L	H290	Met. Corr. 1	-	-	-
				H314	Skin Corr. 1B	≥ 5 %	N	HP8
				H318	Eye Dam. 1	≥ 10 %	N	HP4
LiCl	1–2 %	85144-11-2	Notified C&L	H302	Acute Tox. 4	≥ 25 %	N	HP6
				H315	Skin Irrit. 2	≥ 20 %	N	HP4
				H319	Eye Irrit. 2	≥ 20 %	N	HP4
				H335	STOT SE 3	≥ 20 %	N	HP5
PTFE	0–1 %	12031-82-2	Notified C&L	-	not classified	-	-	-

Annex 6. Overview on electrolytes used in lithium-based batteries

Table 44. An example composition of electrolyte used in lithium-based batteries, with attributed hazards according to CLP (Regulation (EC) No. 1272/2008)

Chemical compound		Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Lithium salts									
$LiPF_6$	Lithium Hexafluorophosphate	1–3 %	21324-40-3	REACH registration C&L	H301	Acute Tox. 3	≥ 5 %	N	HP6
					H314	Skin Corr. 1A	≥ 5 %	Y	HP4
					H318	Eye Dam. 1	≥ 10 %	N	HP4
					H372	STOT RE 1	≥ 1 %	Y	HP5
$LiBF_4$	Lithium Tetrafluoroborate		14283-07-9	REACH registration C&L	H302	Acute Tox. 4	≥ 25 %	N	HP6
					H315	Skin Irrit. 2	≥ 20 %	N	HP4
					H319	Eye Irrit. 2	≥ 20 %	N	HP4
					H341	Muta. 2	≥ 1.0 %	Y	HP11
$LiClO_4$	Lithium Perchlorate		7791-03-9	Notified C&L	H271	Ox. Sol. 1	-	-	-
					H302	Acute Tox. 4	≥ 25 %	N	HP6
					H314	Skin Corr. 1B	≥ 5 %	N	HP8
					H318	Eye Dam. 1	≥ 10 %	N	HP4
					H373	STOT RE 2	≥ 10 %	N	HP5
LiFSl	Lithium bis(fluorosulfonyl)imide		171611-11-3	REACH registration C&L	H302	Acute Tox. 4	≥ 25 %	N	HP6
					H315	Skin Irrit. 2	≥ 20 %	N	HP4
					H318	Eye Dam. 1	≥ 10 %	N	HP4
					H361	Repr. 2	≥ 3.0 %	N	HP10
Organic solvents									
$C_3H_4O_3$	Ethylene carbonate (EC)	10–20 %	96-49-1	REACH registration C&L	H302	Acute Tox. 4	≥ 25 %	N	HP6
					H319	Eye Irrit. 2	≥ 20 %	N	HP4
					H373	STOT RE 2	≥ 10 %	Y	HP5
$C_4H_8O_3$	Ethyl Methyl Carbonate (EMC)		623-53-0	Notified C&L	H225	Flam. Liq. 2	-	-	HP3

$OC(OCH_2CH_3)_2$	Diethyl Carbonate (DC)		105-58-8	REACH registration C&L	H226	Flam. Liq. 3	-	-	HP3
$C_4H_6O_3$	Propylene carbonate (PC)		108-32-7	Harmonised C&L	H319	Eye Irrit. 2	≥ 20 %	N	HP4
$(CH_3O)_2CO$	Dimethyl carbonate (DMC)		616-38-6	Harmonised C&L	H225	Flam. Liq. 2	-	-	HP3
$C_3H_2O_3$	Vinylene Carbonate (VC)		872-36-6	REACH registration C&L	H302 H311 H315 H317 H318 H361 H373 H411	Acute Tox. 4 Acute Tox. 3 Skin Irrit. 2 Skin Sens. 1 Eye Dam. 1 Repr. 2 STOT RE 2 (liver) (oral) Aquatic Chronic 2	≥ 25 % ≥ 15 % ≥ 20 % ≥ 10 % ≥ 10 % ≥ 3.0 % ≥ 10 % ≥ 2.5 %	N °Y N Y Y Y Y Y	HP6 HP6 HP4 HP13 HP4 HP10 HP5 HP14
C_6H_5F	Fluorobenzene		462-06-6	REACH registration C&L	H225 H318 H411	Flam. Liq. 2 Eye Dam. 1 Aquatic Chronic 2	- ≥ 10 % ≥ 2.5 %	- Y Y	HP3 HP4 HP14
LiF_2PO_2	Lithium phosphorodifluoridate		24389-25-1	REACH registration C&L	H301 H312 H314 H318 H372 H411	Acute Tox. 3 Acute Tox. 4 Skin Corr. 1 Eye Dam. 1 STOT RE 1 (Stomach) (oral) Aquatic Chronic 2	≥ 5 % ≥ 55 % ≥ 5 % ≥ 10 % ≥ 1 % ≥ 2.5 %	Y N Y Y Y Y	HP6 HP6 HP8 HP4 HP5 HP14

$F_2LiNO_4S_2$	Lithium bis(fluorosulfonyl)imide		171611-11-3	REACH registration C&L	H302 H315 H318 H341 H361	Acute Tox. 4 Skin Irrit. 2 Eye Dam. 1 Muta. 2 Repr. 2	≥ 25 % ≥ 20 % ≥ 10 % ≥ 1.0 % ≥ 3.0 %	N N Y Y Y	HP6 HP4 HP4 HP11 HP10
$C_3H_6O_3S$	1,3-Propanesultone		1120-71-4	Harmonised C&L	H302 H312 H350	Acute Tox. 4 Acute Tox. 4 Carc. 1B	≥ 25 % ≥ 55 % ≥ 0.1 %	N N Y	HP6 HP6 HP7
C_8H1_2Si	Tetravinylsilane		1112-55-6	REACH registration C&L	H225 H332 H361 H400 H410	Flam. Liq. 2 Acute Tox. 4 Repr. 2 (oral) Aquatic Acute 1 Aquatic Chronic 1	- ≥ 22.5 % ≥ 3.0 % ≥ 25 % ≥ 0.25 %	- N Y N Y	- HP6 HP10 HP14 HP14
$C_2H_4O_4S$	1,3,2-Dioxathiolane 2,2-dioxide		1072-53-3	REACH registration C&L	H302 H314 H317 H318 H351	Acute Tox. 4 Skin Corr. 1 Skin Sens. 1B Eye Dam. 1 Carc. 2	≥ 25 % ≥ 5 % ≥ 10 % ≥ 10 %	N Y Y Y	HP6 HP8 HP 13 HP4
$LiCF_3SO_3$	Lithium trifluoromethanesulfonate (Li-Triflate)		33454-82-9	REACH registration C&L	H302 H319	Acute Tox. 4 Eye Irrit. 2	≥ 25 % ≥ 20 %	N N	HP6 HP4
$LiC_2F_6NO_4S_2$	Lithium bis(trifluoromethanesulfonyl)imide (LiTFSI)		90076-65-6	Harmonised C&L	H301 H311 H314 H373 H412	Acute Tox. 3 Acute Tox. 3 Skin Corr. 1B STOT RE 2 Aquatic Chronic 3	≥ 5 % ≥ 15 % ≥ 5 % ≥ 10 % ≥ 25 %	Y °Y Y Y N	HP6 HP6 HP8 HP5 HP14

$C_4F_{10}LiNO_4S_2$	Lithium bis(pentafluoroethanesulfonyl)imide (LiBETI)		132843-44-8	Notified C&L	not classified	-	-	-	-
$C_6F_3LiN_4$	Lithium 4,5-dicyano-2-(trifluoromethyl)imidazol-1-ide (LiTDI)		761441-54-7	Notified C&L	H301 H318 H412	Acute Tox. 3 Eye Dam. 1 Aquatic Chronic 3	≥ 5 % ≥ 10 % ≥ 25 %	Y Y N	HP6 HP4 HP14
$C_6H_5CF_3$	Trifluorotoluene (TFT)		98-08-8	Harmonised C&L	H225 H411	Flam. Liq. 2 Aquatic Chronic 2	- ≥ 2.5 %	- Y	- HP14
$C_6H_6BF_9O_3$	Tris(2,2,2-trifluoroethyl)borate (TFEB)		659-18-7	Notified C&L	H302 H361 H412	Acute Tox. 4 Repr. 2 Aquatic Chronic 3	≥ 25 % ≥ 3.0 % ≥ 25 %	N Y N	HP6 HP10 HP14
$(C_2H_5O)_2CO$	Diethyl Carbonate (DEC)		105-58-8	REACH registration C&L	H226	Flam. Liq. 3	-	-	-
$C_4H_8O_2$	Ethyl Acetate (EA)		141-78-6	Harmonised C&L	H225 H319 H336	Flam. Liq. 2 Eye Irrit. 2 STOT SE 3	- ≥ 10 % -	- Y -	- HP4 -

Annex 7. Fluorinated substances found in lithium-bases batteries

Table 45. Examples of fluorinated substances found in lithium-based batteries with their CAS numbers and with hazard identification according to CLP (1272/2008) (Rensmo et al., 2023)

Chemical compound		CAS No.		Hazard statement code	
Fluorinated binders and separators					
PVDF	Polyvinylidene fluoride	24937-79-9	Notified C&L	-	not classified
PVDF	Polyvinylidene fluoride	24937-79-9	Notified C&L	H315 H319 H335	Skin Irrit. 2 Eye Irrit. 2 STOT SE 3
PVDF-HFP	Polyvinylidene fluoride co-hexafluoropropylene	9011-17-0	Notified C&L	H411	Aquatic Chronic 2
PVDF-TrFE	Polyvinylidene fluoride co-trifluoroethylene	Not found	-	-	-
PTFE	Polytetrafluoroethylene	9002-84-0	Notified C&L	-	not classified
FEP	Fluorinated ethylene propylene	25067-11-2	Notified C&L	-	not classified
Fluorinated salt and salt additives					
$LiPF_6$	Lithium hexafluorophosphate	21324-40-3	REACH registration C&L	H301 H314 H318 H372	Acute Tox. 3 Skin Corr. 1A Eye Dam. 1 STOT RE 1
$LiAsF_6$	Lithium hexafluoroarsenate	29935-35-1	Notified C&L	H301 H331 H400 H410	Acute Tox. 3 Acute Tox. 3 Aquatic Acute 1 Aquatic Chronic 1
$LiBF_4$	Lithium tetrafluoroborate, anhydrous	14283-07-9	REACH registration C&L	H302 H315 H319 H341	Acute Tox. 4 Skin Irrit. 2 Eye Irrit. 2 Muta. 2
LiFSI	lithium bis(fluorosulfonyl)imide	171611-11-3	REACH registration C&L	H302 H315 H318 H361	Acute Tox. 4 Skin Irrit. 2 Eye Dam. 1 Repr. 2
LiFTFSI	lithium fluorosulfonyl-trifluorosulfonyl imide	192998-62-2	Notified C&L	H314 H318	Skin Corr. 1B Eye Dam. 1
LiTFSI	lithium bis(trifluoromethylsulfonyl)imide	90076-65-6	Harmonised C&L	H301 H311	Acute Tox. 3 Acute Tox. 3

				H314 H373 H412	Skin Corr. 1B STOT RE 2 Aquatic Chronic 3
LiDFOB	lithium difluoro(oxalate)borate	409071-16-5	REACH registration C&L	H315 H318 H400 H410	Skin Irrit. 2 Eye Dam. 1 Aquatic Acute 1 Aquatic Chronic 1
LiBETi	lithium bis(perfluoroethanesulfonyl)imide	132843-44-8	Notified C&L	-	not classified
Tri-flate	-	-	Not found	-	-
Advanced fluorinated salt additives					
LiFAP	lithium tri(pentafluoroethyl)triphosphate	-	Not found	-	-
LiFAP	lithium tri(pentafluoroethyl)triphosphate	-	Not found	-	-
Fluorinated solvent additives					
FEC	fluoroethylene carbonate	114435-02-8	REACH registration C&L	H302 H315 H317 H319 H372	Acute Tox. 4 Skin Irrit. 2 Skin Sens. 1 Eye Irrit. 2 STOT RE 1
DFEC	difluoroethylene carbonate	171730-81-7	Notified C&L	H302 H315 H317 H319	Acute Tox. 4 Skin Irrit. 2 Skin Sens. 1 Eye Irrit. 2
TFPC	trifluoropropylene carbonate	167951-80-6	Notified C&L	H315 H319 H335	Skin Irrit. 2 Eye Irrit. 2 STOT SE 3
MDFA	methyl difluoroacetate	433-53-4	Notified C&L	H226 H302 H312 H315 H319 H332 H335	Flam. Liq. 3 Acute Tox. 4 Acute Tox. 4 Skin Irrit. 2 Eye Irrit. 2 Acute Tox. 4 STOT SE 3
F-EPE	tetrafluoroethyl tetrafluoropropylether	16627-68-2	Notified C&L	H225	Flam. Liq. 2

Annex 8. Chemical compounds formed during electrochemical processes in Li-$SOCl_2$

Table 46. Chemical compounds that are formed during electrochemical processes in Li-$SOCl_2$ with hazard identification according to CLP (1272/2008)

Reaction products	Weight (% total battery)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
H_2	unknown	-	-	-	-	-	-	-
Li_2O	unknown	12057-24-8	REACH registration C&L	H314 H318 H331	Skin Corr. 1B Eye Dam. 1 Acute Tox. 3	≥ 1 % and < 5 % ≥ 10 % ≥ 3.5 %	°N - -	HP8 - -
LiOH	unknown	1310-66-3	Notified C&L	H302 H314	Acute Tox. 4 Skin Corr. 1B	≥ 25 % ≥ 1 % and < 5 %	- -	- -
Cl_2	unknown	7782-50-5	Harmonised C&L	- H270[68] H315 H319 H331 H335 H400	Press. Gas Ox. Gas 1 Skin Irrit. 2 Eye Irrit. 2 Acute Tox. 3 STOT SE 3 Aquatic Acute 1	- 0.1 % ≥ 5 % ≥ 20 % ≥ 3.5 % ≥ 20 % ≥ 25 %	- - - - - - -	- - - - - - -
SO_2	unknown	13450-90-3	REACH registration C&L	H281 H314 H331	Press. Gas (Comp.) Skin Corr. 1B Acute Tox. 3	- ≥ 1 % and < 5 % ≥ 3.5 %	- - -	- - -

[68] Where a waste contains a substance assigned H270 it is possible to calculate whether or not the waste displays HP2. The calculation method is provided by ISO 10156 (as amended) and should be applied in accordance with the ECHA CLP Guidance

S_2Cl_2	unknown	10025-67-9	Harmonised C&L	H301 H314 H332 H400	Acute Tox. 3 Skin Corr. 1A Acute Tox. 4 Aquatic Acute 1	≥ 5 % ≥ 10 % ≥ 22.5 % ≥ 25 %	- - - -	- - - -
HCl	unknown	7647-01-0	Multiple harmonised classification	H314 H335	Skin Corr. 1B STOT SE 3	≥ 10 % ≥ 20 %	- -	- -

Annex 9. Chemical compounds formed during electrochemical processes in zinc-based batteries

Table 47. Overview on reaction products of zinc-based batteries with hazard identification according to CLP (1272/2008)

Chemical compound		CAS No.	Source	Hazard statement code, hazard class and category code	
Zinc carbon					
MnO(OH)	Manganese oxide-hydroxide	not found	-	-	-
$Zn(NH_3)_2Cl_2$	Diamminedichloridozinc(II)	14639-97-5[69]	REACH registration C&L	H302 H318 H400 H410	Acute Tox. 4 Eye Dam. 1 Aquatic Acute 1 Aquatic Chronic 2
Mn_2O_3	Di-manganese tri-oxide	1317-34-6	REACH registration C&L	-	not classified
Zinc chloride					
$Zn(OH)_2$	Zinc hydroxide	20427-58-1	REACH registration C&L	H400 H411	Aquatic Acute 1 Aquatic Chronic 2
Zinc air					
ZnO	Zinc oxide	1314-13-2	Harmonised C&L	H400 H410	Aquatic Acute 1 Aquatic Chronic 1
Ag(I)O	Silver (I) oxide	11113-88-5	Notified C&L	H272 H315 H319 H335	Ox. Sol. 2 Skin Irrit. 2 Eye Irrit. 2 STOT SE 3
Ag(II)O	Silver (II) oxide	1301-96-8	Notified C&L	H272 H315 H319 H335	Ox. Sol. 2 Skin Irrit. 2 Eye Irrit. 2 STOT SE 3
$Zn(OH)_2$	Zinc hydroxide	20427-58-1	REACH registration C&L	H400 H411	Aquatic Acute 1 Aquatic Chronic 2
ZnO	Zinc oxide	1314-13-2	Harmonised C&L	H400 H410	Aquatic Acute 1 Aquatic Chronic 1

[69] C&L inventory provides information only on Diammonium tetrachlorozincate $^{(2-)}$ with CAS No. 14639-97-5.

Annex 10. Reaction products of sodium-sulphur batteries

Table 48. Overview on reaction products of sodium-sulphur batteries with hazard identification according to CLP (1272/2008)

Chemical compound	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Na_2S	1313-82-2	Harmonised C&L	H302 H311 H314 H400	Acute Tox. 4 Acute Tox. 3 Skin Corr. 1B Aquatic Acute 1	≥ 25 % ≥ 15 % ≥ 5 % ≥ 25 %	- - - -	HP6 HP6 HP4 HP14
Na_2S_4	12034-39-8	Notified C&L	H228 H314	Flam. Sol. 2 Skin Corr. 1B	- ≥ 15 %	- -	- HP6

Annex 11. Chemical compounds in precipitated metal salts from black mass treatment

Table 49. Chemical compounds, in precipitated metal salts from black mass treatment with hazard identification according to CLP (1272/2008)

Chemical compound	Weight (%)	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
$NiSO_4$	unknown	10101-97-0	Notified C&L	H302 H315 H317 H332 H334 H341 H350 H360 H372 H400 H410	Acute Tox. 4 Skin Irrit. 2 Skin Sens. 1 Acute Tox. 4 Resp. Sens. 1 Muta. 2 Carc. 1A Repr. 1B STOT RE 1 Aquatic Acute 1 Aquatic Chronic 1	≥ 25 % ≥ 20 % ≥ 10 % ≥ 22.5 % ≥ 10 % ≥ 1.0 % ≥ 0.1 % ≥ 0.3 % ≥ 1 % ≥ 25 % ≥ 0.25 %	- - - - - - - - - - -	HP6 HP4 HP13 HP6 HP13 HP11 HP7 HP10 HP5 HP14 HP14
$Ni(OH)_2$	unknown	12054-48-7	Harmonised C&L	H302 H315 H317 H332 H334 H341 H372 H400 H410 H350i H360D	Acute Tox. 4 Skin Irrit. 2 Skin Sens. 1 Acute Tox. 4 Resp. Sens. 1 Muta. 2 STOT RE 1 Aquatic Acute 1 Aquatic Chronic 1 Carc. 1A Repr. 1B	≥ 25 % ≥ 20 % ≥ 10 % ≥ 22.5 % ≥ 10 % ≥ 1.0 % ≥ 1 % ≥ 25 % ≥ 0.25 % ≥ 0.1 % ≥ 0.3 %	- - - - - - - - - - -	HP6 HP4 HP13 HP6 HP13 HP11 HP5 HP14 HP14 HP7 HP10
$CoSO_4$	unknown	12034-39-8	Harmonised C&L	H302 H317 H334 H341 H400 H400i H350i H360F	Acute Tox. 4 Skin Sens. 1 Resp. Sens. 1 Muta. 2 Aquatic Acute 1 Aquatic Chronic 1 Carc. 1B Repr. 1B	≥ 25 % ≥ 10 % ≥ 10 % ≥ 1.0 % ≥ 25 % ≥ 25 % ≥ 0.1 % ≥ 0.3 %	- - - - - - - -	HP6 HP13 HP13 HP11 HP14 HP14 HP7 HP10
$Co(OH)_2$	unknown	21041-93-0	REACH registration C&L	H302 H317 H319	Acute Tox. 4 Skin Sens. 1 Eye Irrit. 2	≥ 25 % ≥ 10 % ≥ 20 %	- - -	HP6 HP13 HP4

				H330 H334 H350i H360Fd H400 H411	Acute Tox. 1 Resp. Sens. 1B Carc. 1B Repr. 1B Aquatic Acute 1 Aquatic Chronic 2	≥ 0.1 % ≥ 10 % ≥ 0.1 % ≥ 0.3 % ≥ 25 % ≥ 0.25 %	- - - - - -	HP6 HP13 HP7 HP10 HP14 HP14
$MnSO_4$	unknown	7785-87-7	Harmonised C&L	H373 H411	STOT RE 2 Aquatic Chronic 2	≥ 10 % ≥ 2.5 %	- -	HP5 HP14
$Mn(OH)_2$	unknown	21041-93-0	REACH registration C&L	H302 H317 H319 H330 H334 H350i H360Fd H400 H411	Acute Tox. 4 Skin Sens. 1 Eye Irrit. 2 Acute Tox. 1 Resp. Sens. 1B Carc. 1B Repr. 1B Aquatic Acute 1 Aquatic Chronic 2	≥ 25 % ≥ 10 % ≥ 20 % ≥ 0.1 % ≥ 10 % ≥ 0.1 % ≥ 0.3 % ≥ 25 % ≥ 0.25 %	- - - - - - - - -	HP6 HP13 HP4 HP6 HP13 HP7 HP10 HP14 HP14

Annex 12. Chemical compounds in concentrates recycled from NCA, NMC and LFP manufacturing waste

Table 50. Concentrates recycled from NCA, NMC and LFP battery manufacturing waste, their chemical compounds and the % share on the total battery mass

Input	NCA	NMC	LFP	CAS No.	Source	Hazard statement code, hazard class and category code		Conc. limit	Haz. Class. (Y/N/°)	H (WFD Annex III)
Chemical compound	Weight (%)									
Al-Co-Li-Ni-oxide	≥ 60 %	-	-	177997-13-6	REACH registration C&L	H314 H317 H330 H334 H350 (inh.) H360 H372 (lungs) H412	Skin Corr. 1B Skin Sens. 1 Acute Tox. 2 Resp. Sens. 1 Carc. 1A Repr. 1B STOT RE 1 Aquatic Chronic 3	≥ 1 % and < 5 % ≥ 5 % ≥ 10 % ≥ 0.1 % ≥ 0.1 % ≥ 0.3 % ≥ 1 % ≥ 25 %	Y Y Y Y Y Y Y Y	HP8 HP13 HP6 HP13 HP7 HP10 HP5 HP14
Co-Li-Mn-Ni-oxide	-	≥ 60 %	-	182442-95-1	Notified C&L	H330 H350 H372 H412	Acute Tox. 2 Carc. 1B STOT RE 1 Aquatic Chronic 3	≥ 0.1 % ≥ 0.1 % ≥ 1 % ≥ 25 %	Y Y Y Y	HP6 HP7 HP5 HP14
Phosphoric acid, iron ($^{2+}$) lithium salts (1:1:1)	-	-	≥ 60 %	15365-14-7	Notified C&L	-	not classified	-	-	-
Graphite	≤ 40 %	≤ 40 %	≤ 40 %	7782-42-5	REACH registration C&L	-	not classified	-	-	-

Aluminium (powder)	≤ 5 %	≤ 5 %	≤ 5 %	7429-90-5	Multiple harmonised classifications	H228 H261	Pyr. Sol. 1 Water-react. 2	No conc. limit 0.1 %	– Y	– HP3
Aluminium (massive)	≤ 5 %	≤ 5 %	≤ 5 %	7429-90-5	Notified C&L	–	not classified	–	–	–
Copper (granulated copper; particle length: from 0.9 mm to 6.0 mm; particle width: from 0.494 to 0.949 mm)	≤ 5 %	≤ 5 %	≤ 5 %	7440-50-8	Harmonised C&L	H411	Aquatic Chronic 2	≥ 2.5 %	°Y	HP4

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