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Facilitating Circularity in the Lithium-ion Battery Value Chain by Designing for Recycling

Master's thesis in Industrial Design Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Lithium-ion batteries push electrification forward, and the volume rapidly increases on a global scale. The growing demand adds pressure to obtain materials such as cobalt, nickel, manganese, and lithium –the most critical compounds of cell chemistry and not carefree materials from a sustainability view. The increasing demand may also add pressure on recycling and material recovery in order to secure the scarce and valuable materials. However, there are difficulties in recycling lithium-ion batteries today due to battery pack constructions which may prevent material recovery. These issues risk following into the future if actions are not taken.

This master's thesis investigates the lithium-ion battery pack construction from an industrial design engineering approach by integrating the topic with circular design strategies. The focus of the study is electric vehicle batteries on the European market. The lithium-ion battery constraints and the value chain are explored to empathize with the subject holistically. The aim is to promote circularity by facilitating recycling to reduce environmental impacts and minimize the value-loss at the product's end-of-life. Therefore, the thesis collects facilitating factors for recycling lithium-ion batteries and compiles them into design guidelines for use in the design phase. Based on the fact that 80% of a product's total environmental impact is determined at the design phase, including the product's recyclability.

- *"Problem är vår uppgift; vi tar itu med dem för att överleva eller för att förbättra världen, och därför är det bättre att se dem i vitögat än att titta bort, gömma undan dem och förneka dem. Att se problemen i vitögat kan vara en hoppfull handling, men bara om man kommer ihåg att de inte är det enda som finns".*

  - Rebecka Solnit, 2017.

Keywords: Design for Recycling; Eco-Design; Circular Economy; Lithium-ion Battery Value Chain; Lithium-ion Batter Recycling; Lithium-ion Module Pack Design.

Nomenclature

LIBs	Lithium-ion Batteries
Li-ion	Lithium-ion
EV	Electrical Vehicle
OEM	Original Equipment Manufacturer
EoL	End of Life
PCB	Printed Circuit Board
SoC	State of Charge
SoH	State of Health
HW	Hardware
SW	Software
Battery Cell Chemistries:	
NCA	Lithium-nickel-cobalt-aluminum oxide (LiNiCoAlO2)
NMC	Lithium-nickel-manganese-cobalt oxide (LiNiMnCoO2)
LCO	Lithium-cobalt oxide (LiCoO2)
LFP	Lithium-iron phosphate (LiFePo)
LMO	Lithium-manganese oxide (LiMn2O4)
DfR	Design for Recycling
DfE	Design for Environment.
LCA	Life Cycle Assessment
Virgin Material	Previously unused raw material
Thermal Runaway	An accelerating chemical process where increased temperature releases energy, which increases the temperature to release energy and so on further.

TABLE OF CONTENT

1

INTRODUCTION

This part introduces the thesis topic by describing the background, problematization, and thesis aim. It also describes the objectives and research questions as well as the output deliverables. The chapter is summed up by a reader's guide showing the thesis outline.

1.1 Background

The electricity demand is growing globally (Eia, 2020). At the same time, lithium-ion batteries are taking a leading position towards electrification, which results in an increased battery demand and rapidly growing volumes worldwide (Stevens, 2019) (Irle, 2020). Today, batteries are used in various applications such as tools, vehicles, and energy storage systems. The increased demand adds pressure on the environment and natural resources. Environmental impact occurs throughout the life cycle, from material extraction and refining to battery manufacturing, usage, and end of life. According to the Swedish Environmental Research Institute, the most prominent emission of lithium-ion batteries relates to the production methods and the used type of energy resource at the time of writing (IVL, 2019). The latter since it is still unusual to use green energy for battery cell production as writing. The batteries also contain valuable and critical materials, such as lithium related to environmental issues and cobalt connected to poor working conditions and child labor through artisan mining in the Democratic Republic of Congo (Bloomberg Technology, 2020). Recycling will be essential to cope with the increased demand for lithium-ion batteries to secure scarce and valuable raw materials (Gratz, Sa, Apelian, & Wang, 2014). Furthermore, volume growth increases the pressure on current recycling infrastructures, which need to be developed and equipped to cope with future waste volumes (Karlsson & Lindström, 2018).

Several initiatives are emerging to improve these circumstances. For example, the Swedish battery manufacturer Northvolt claims to distribute the world's greenest battery in 2022 by using renewable energy in their production (Northvolt, 2020). In addition, ongoing research is trying to replace battery materials, and other efforts push to ensure sustainable material flows through blockchain. The initiatives are many and concern ethical, ecological, and societal aspects. Below are a few more examples of these:

- The EU's Green Deal is an initiative planning to make the EU the world's first climate-neutral continent by 2050 (European Commission, 2021a). The plan is ensured through a so-called Green Taxonomy, where various financial instruments direct capital flows towards a sustainable economy (Astberg, 2021). One example of this is the EU post-covid-19 recovery fund, where 37% of the finances are devoted to green investments.
- Stricter battery legislation is expected through an updated EU Batteries Directive replacing the older EU Batteries Directive of 2006/66 / EC (EUR-Lex, 2020). The revised Directive proposal is under consultation at the time of writing and expects to enter into force 1st of January 2022 with a gradual implementation as of 2023 (Mathieu, 2021). The proposal sets higher demands on battery recycling compared to the previous version.

1.2 Problematization

In general, consumption increases globally, and materials demand grows simultaneously (Stena Recycling, 2021). The increased need by the year 2050 for some of the most important materials is shown in table 1 (Stena Recycling, 2021). Materials extraction and production consume a lot of energy, and choosing recycled materials over virgin materials (unused raw material) can save a predominant amount of energy, see table 2 (Stena

Recycling, 2021). Some of the mentioned materials in tables 1 and 2 are common in lithium-ion battery pack construction, such as aluminum and plastics.

Table 1. Expected increase of demand by 2050 (Stena Recycling, 2021).

MATERIAL	INCREASED DEMAND 2050
Aluminum	*3,4
Steel	*2,3
Plastic	*4,2

Table 2. Saved energy by using recycled material compared to virgin material (Stena Recycling, 2021).

MATERIAL	ENERGY SAVED RECYCLED VS VIRGIN
Aluminum	95%
Iron	87%
Glass	40%
Paper	37%
Plastic	37%

The demand for specific lithium-ion battery materials also increases, as earlier mentioned. The most significant assets of necessary lithium-ion battery materials are controlled and originate outside EU borders (Berg, 2018). As the battery demand increase, these materials risk becoming scarce on the European market. But even though Europe seems to lack easily accessible assets at the time of writing, all the materials are already represented in Europe's waste streams and garbage dumps (Berg, 2018). Therefore, urban mining can become a strategy to secure material resources. In fact, battery recycling, in general, may be essential to cope with the increased materials demand worldwide, both from the point of assets but also from a sustainable point of view. But batteries are somewhat difficult to recycle. Batteries are tightly enclosed in casings and are challenging to disassemble (Edström, 2021). The batteries are often exposed to physical stress such as shock and vibration, especially when mounted in vehicles. Therefore, the strong fixation creates a robust construction, but it also complicates disassembly and recycling. Since the demand for batteries increases and volumes go up, material resources and recycling may become a growing issue.

1.3 Aim

Around 80 percent of a product's environmental impact is determined at the design stage (Circular Sweden, 2021). The possibility to recycle a product is also decided in this stage (Stena Recycling, 2021). This master thesis aims to search for facilitating factors for recycling lithium-ion batteries and convert them into design guidelines for use in the design phase of lithium-ion battery pack solutions. Thus, this master thesis seeks to facilitate the recycling of lithium-ion batteries to reduce the environmental impacts, minimize the value-loss at the product's end-of-life, and strive towards circularity.

1.4 Process Strategy and Research Questions

The investigation is performed from an industrial design discipline approach, and the thesis is divided into two phases inspired by the Double Diamond design process. An adapted course of the process is represented in figure 1 (Design Council, 2019). The first phase explores the current situation and gathers essential information, mainly through literature studies and expert interviews. The second phase aims to create the design guidelines based on insights from phase one and is evaluated through expert reviews. Since the project is divided into two phases, so are the research questions to fit into the scope.

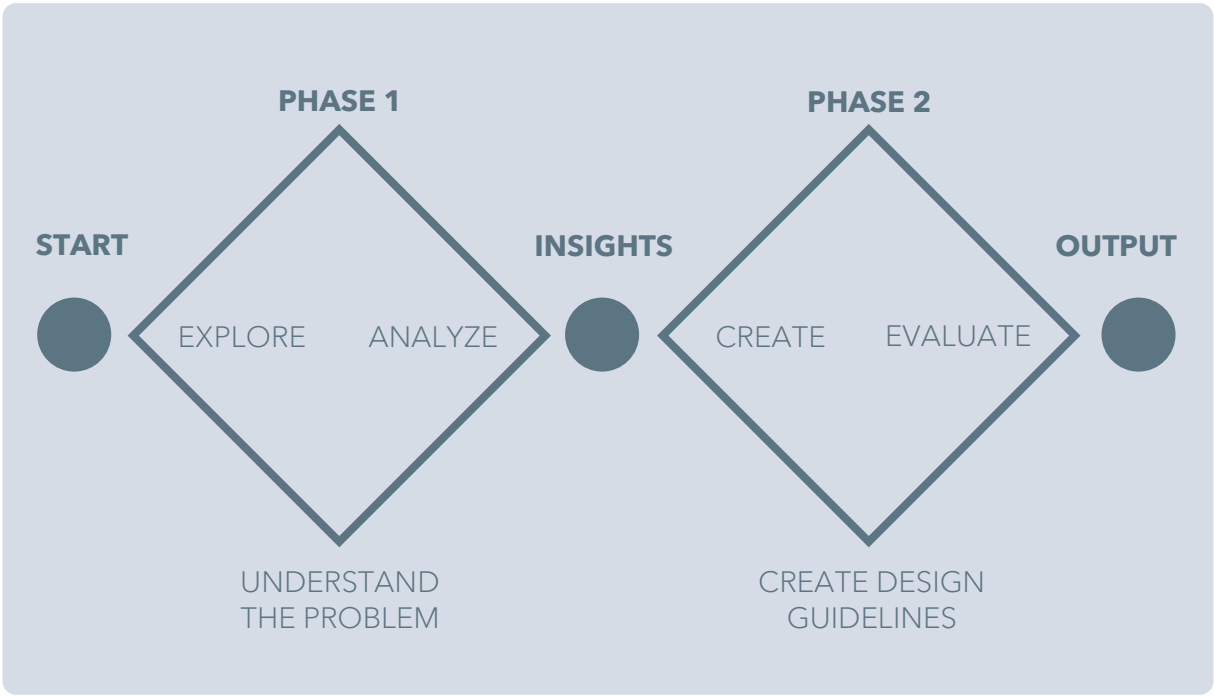


Figure 1. The double diamond design process, adapted from (Design Council, 2019).

1.4.1 Research Questions Phase 1.0

RQ1.1: How is recycling achieved today for the most common lithium batteries from larger applications as vehicles, and how is it expected to take place in the future?
a) Who are the biggest actors in recycling today, and who are expected to be so in the future?
b) Do the needs differ between different recycling actors?

RQ1.2: What factors are central to facilitate and enable the recycling of lithium-ion batteries?
a) From a broader perspective, what factors are linked to transport, handling, disassembly, and the recycling strategy?
b) From a narrow perspective, are there determining aspects related to form factors and cell chemistry linked to recycling?

(Phase 1 creates a framework of requirements for the continued work)

1.4.2 Research Questions Phase 2.0

RQ2.1: How can a battery pack be designed to facilitate the recycling of lithium-ion batteries? Based on the knowledge gained during Phase 1 and the sustainability aspects of eco-friendliness, ethicality, and economy.

1.5 Demarcations

As part of the process, the constraints and the value chain of Li-ion batteries are studied and presented to provide an overall understanding required to establish the design guidelines. The battery value chain is somewhat complex, and the thesis study is limited, as shown in figure 2. Limitations are further presented in the following sections and covers; *Battery Configuration, Types, and Chemistries, Reuse, Markets, Materials*, and the *BMS (Battery Management System).*

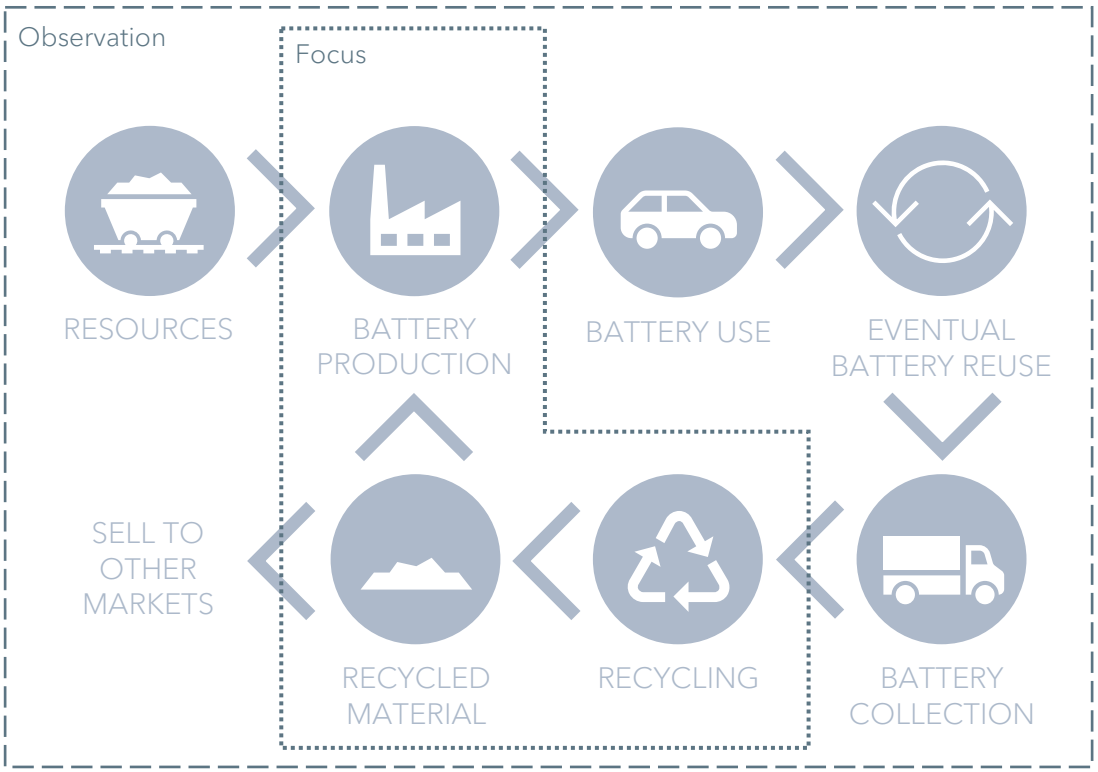


Figure 2. The thesis observation- and focus area, adapted from (Karlsson & Lindström, 2018).

Reuse
Reuse is a connected approach to recycling and an essential strategy for circularity, but this thesis does not treat reuse directly. This delimitation enables an increased focus on recycling, which is vital since, despite eventual reuse, all batteries reach the end of life one day when they must be recycled.

Battery Configuration, Types, and Chemistries
A battery system can be divided into different configurations, such as system, pack, and cell. The thesis primarily focuses on the module and system levels. However, the cell level is described since it sets some of the constraints.

The thesis will not cover battery cell design. Instead, existing information on cell design has been used as a constraint by considering the physical cell shape (further related to type) and battery chemistries. The most common li-ion battery cell types are cylindrical-, prismatic- and pouch-cells (Aurbach & Choi, 2016). The thesis focuses on the most common li-ion battery chemistries, which are investigated briefly concerning recycling. The chemistries are NMC, LFP, LCO, NCA, and NMO (Zackrisson, 2017).

Markets
The thesis mainly focuses on the Swedish and European markets. Other markets are involved due to resource and material flow relations.

Materials
Some of the ethical examples explained in the background chapter are very complex. It is therefore not possible to cover them thoroughly through the scope of this thesis.

BMS
BMS (Battery Management System) and associated PCB (Printed Circuit Boards) with components and software will not be covered. The thesis will only treat these subjects briefly in terms of physical shape and material.

1.6 Deliverables

The thesis has resulted in a substantial amount of compiled information which is represented in chapter *4. COMPILATION OF INFORMATION GATHERING,* and chapter *5. VALUE CHAIN*. In addition, the work has also resulted in design guidelines. These guidelines are created by combining the compiled data and the conclusions and evaluations made during the thesis process. The guidelines relevance are evaluated by a smaller group of professionals in the Swedish lithium-ion battery industry. The guidelines are represented in chapter *6. DESIGN GUIDELINES*.

1.7 Thesis Outline

The following list is a readers' guide describing the thesis chapters in short:

1. INTRODUCTION	Introduce the reader to the topic and aim as well as the problematization.
2. THEORY	Introduce the reader to circular product development and design strategies.
3. METHOD	Describes the methods used and the work pathway utilized to conduct the thesis.
4. COMPILATION OF INFORMATION	Information gathering has been a significant part of the thesis work. This chapter compiles the information of the topic and may be seen as part of the result. The chapter covers the subchapters stated below, which may be read individually and selectively based on the reader's expertise. 4.1 Li-Ion Batteries 4.2 Legislation 4.3 Recycling Electronic Waste 4.4 Recycling Li-Ion Batteries 4.5 Li-Ion in the Future
5. VALUE CHAIN	The chapter maps out a theoretical life cycle for an electric vehicle. It describes the value chain activities with a particular focus on factors relevant to recycling.
6. DESIGN GUIDELINES	This chapter presents a suggestion of design guidelines aimed to be used in the development phase of li-ion battery packs to promote recycling at the product's end of life, to increase material recovery and circularity.
7. DISCUSSION	This chapter discuss the thesis elements and answers the research questions. It also suggests topics for further work.
8. CONCLUSION	This chapter summarizes the findings in relation to the thesis aim and discusses them in the broader perspective.

2

THEORY

This chapter provides a theoretical background and base knowledge by addressing design strategies for circular product development (design for recycling in particular) and explaining their integration into the product development process.

2.1 Circular Economy

The circular economy is often referred to as a closed-loop, contrary to the so-called linear economy. The linear economy makes methodical resource extraction, followed by processing and usage, to form waste (Stena Recycling, 2021), shown in figure 3.

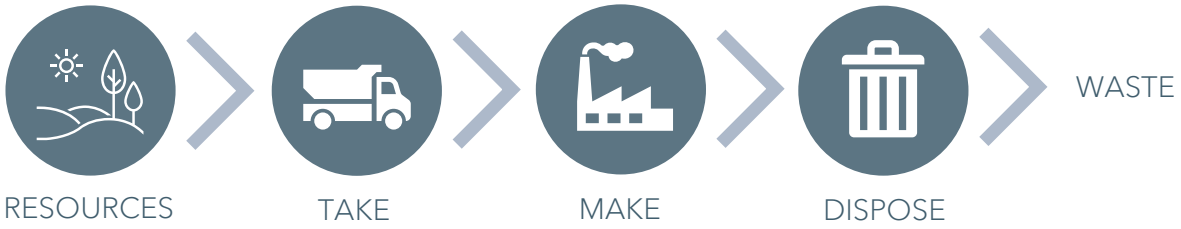


Figure 3. Linear economy, adapted from (Ellen MacArthur Foundation, 2018).

A circular economy keeps resources in use, regenerates natural systems, and designs away waste and pollution through business and design principles (Ellen MacArthur Foundation, 2017a). The foundation of Circular Economy was initiated in the 1990s by Robert Ayres, who introduced the "industrial metabolism" (Bakker, Bocken, de Pauw, & van der Grinten, 2016). Later, Michael Brungart and William McDonough established the importance of closing both the technical and biological loop in their theory "cradle-to-cradle." According to the Ellen Mc Arthur Foundation, Circular Economy is about rebuilding value, aiming at everything from finances, manufacturing, human, social, and nature (Ellen MacArthur Foundation, 2017a). Figure 4 visualize circular economy through a constant flow of technical materials (to the right) and biological materials (to the left).

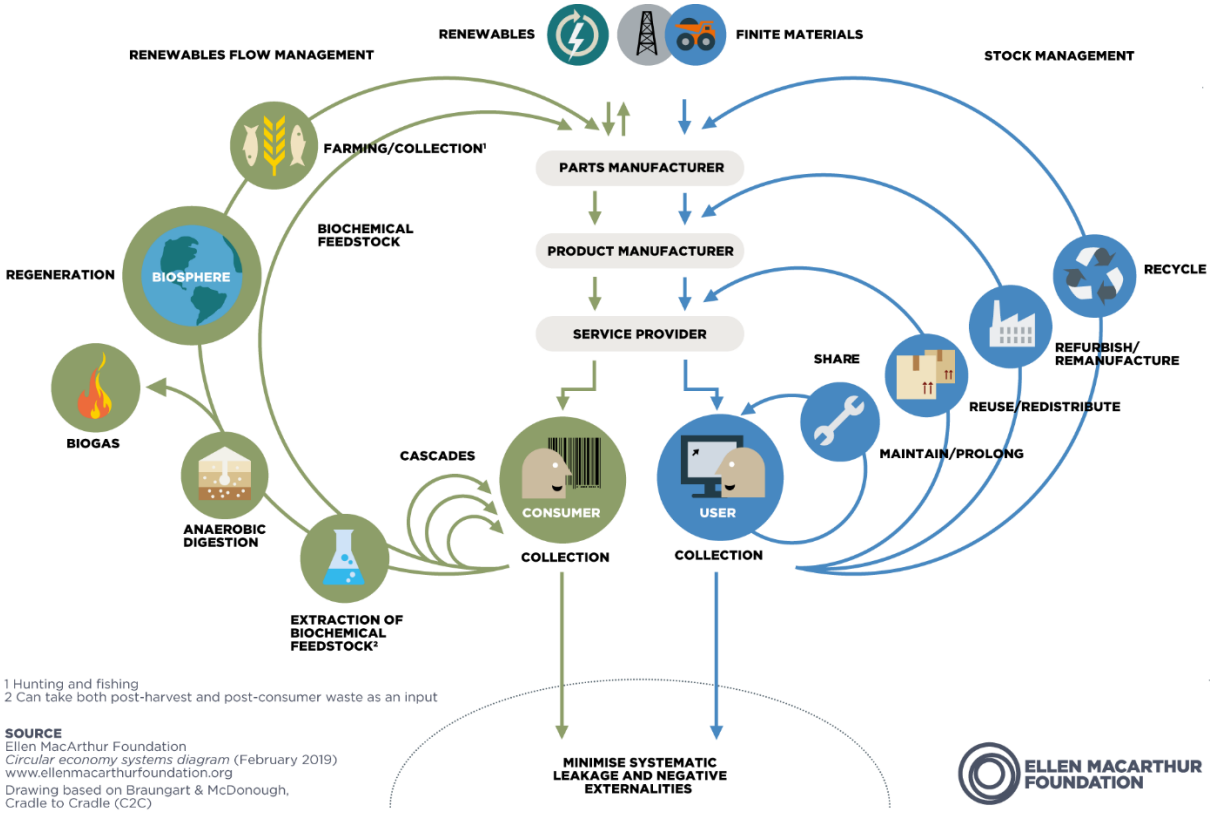


Figure 4. The circular economy system diagram (Ellen MacArthur Foundation, 2017a). Printed with permission from the Ellen McArthur Foundation www.ellenmcarthurfoundation.org

Circular economy aims to minimize resource usage to reduce the ecological footprint, which is beneficial for society, companies, and individuals (Selverfors, 2021). A circular economy requires changes to the whole system from business to products and consumption. The design must eliminate waste generation and unnecessary resource use.

Companies face challenges in transitioning from linear to circular business models (Bakker, Bocken, de Pauw, & van der Grinten, 2016). Bakker, C et al. (2016) investigate strategies for product design and business models for a circular economy in the literature and suggest a framework to follow for the transition in table 3. They also claim that the design strategies and the business models need to be integrated rather than used separately. The circular product design strategies and especially the closing loop strategies, marked in bold in table 3 below, are especially essential for the thesis scope.

Table 3. Circular economy product and business model strategy framework adapted from (Bakker, Bocken, de Pauw, & van der Grinten, 2016).

VISIONARY STATEMENT GOALS e.g., realize circular designs; challenge planned obsolescence or challenge unsustainability	
Circular product design strategies: Slowing loop • Designing long-life products • Design for product-life extension **Closing loop** • **Design for a technological cycle** • **Design for a biological cycle** • **Design for dis- and reassembly**	Circular business model strategies: Slowing loop • Access and performance model • Extending product value • Classic long life • Encourage sufficiency Closing loop • Extending resource value • Industrial Symbiosis

2.2 Circular Design

Design for Environment, Design for Sustainability, Eco Design, and Circular Design are all phrases of the same methods, more or less, which all have the overall goal to minimize products' environmental impact. According to Anna Vetlander Gisslén, project and communications manager in the EU-funded EcoDesign Circle, circular design is about closing loops to maintain resources (Gisslén, 2021). Research has also found that it is possible to improve both costs and quality by applying circular approaches. Companies that adopt these design strategies strategically and innovatively tend to get higher profit margins over extended periods (Gisslén, 2021).

All products have some environmental impact. Eppinger & Ulrich (2012) define Design for Environment (DfE) as a product development process to minimize the environmental impacts and strive towards a more sustainable society. According to Eppinger & Ulrich (2012), the environmental impact refers to:

- **Global Warming** – The global temperatures are rising due to emissions of greenhouse gasses.
- **Resource Depletion** – Nonrenewable and limited materials
- **Solid Waste** – Products generate waste. Some get recycled. Others do not and then get resolved in incineration and landfill.
- **Water Pollution** – Most significant source of pollution is disposals from industrial processes and can contain heavy metals, fertilizers, solvents, oils, acids, etc.
- **Air Pollution** – Sources of pollution are factories, power plants, incinerators, residential and commercial buildings, and vehicles.
- **Land degradation** – The effects caused by the extraction of materials.
- **Biodiversity** – The variety of plants and animals.
- **Ozone Depletion** – Ozone degradation due to emissions.

Life cycle thinking is vital in circularity. Exploring the life cycle provides an overview and creates a broad understanding of the situation (University of Cambridge, 2021). According to the cradle-to-cradle approach, the life cycle can be divided into two loops, the biological- and the technological loop (Eppinger & Ulrich, 2012), as earlier visualized in figure 4. A product may fit in the biological- or the technical loop, or both. The latter is sometimes referred to as the "monstrous hybrid" since different materials can hinder materials recovery. Eventual losses should be compatible with biological systems in the biological loop. Other materials must be recycled and adapted to the technical loop. To take a more holistic approach, McDonugh and Brungarts introduce three main strategies for circular product design, adopted by (Eppinger & Ulrich, 2012):

- **Materials Chemistry** – What is the chemical content of the material? Safe for humans and the environment?
- **Disassembly** – Can the product be disassembled to recycle the materials?
- **Recyclability** – Content of recycled materials?; Separable into recycling categories?; Can the material be recycled?

Another commonly addressed approach in circularity is the so-called waste hierarchy, an EU Directive working as a guide for handling waste to minimize its environmental impacts, see figure 5 (European Commission, 2021b).

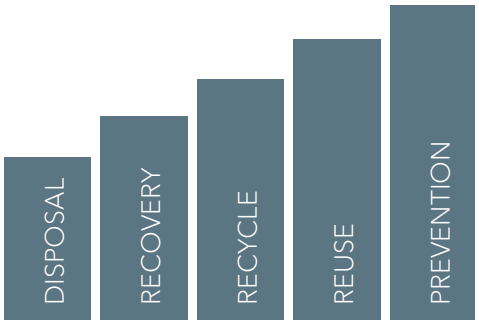


Figure 5. The EU Waste Hierarchy (European Commission, 2021b).

A similar approach to the EU waste hierarchy is the 5 R's of Zero Waste: Refuse, Reduce, Reuse, Recycle, and Rot. It is argued that the 5R's reached popularity after being declared in the book *Zero Waste Home* by Bea Johnson in 2013 (Chapman, 2017). Since then, the R's have continued to evolve and now include about 7-11 R's depending on how presented (Ellen MacArthur Foundation, 2017b) (Zerowasteliving, 2020). Some of these are stated in table 4.

Table 4. 11 R's, adapted from (Bakker, Bocken, de Pauw, & van der Grinten, 2016), (Ellen MacArthur Foundation, 2017b), (Zerowasteliving, 2020).

11 R's	
Refuse	– consider if the function is needed at all, refrain or solve the need in another way.
Rethink	– intense use, e.g., by using it for more tasks or sharing a product.
Reduce	– use fewer/less natural resources, materials, energy, etc.
Reuse	– reused in new possession and used by another consumer.
Repair	- service and maintenance to restore function.
Refurbish	– reconstruct something old to bring it up to date.
Remanufacture	– use parts in a new product with the same function.
Repurpose	– put in another use.
Recycle	– material recovery process to obtain the same quality or lower quality (downcycled).
Rot	– biodegrading by, for example, fungi, microorganisms, and bacteria. E.g., composting.
Recover (Energy)	– Incineration to extract energy from the materials

2.3 Design for Recycling

A study released in January of 2021 shows that only 8,6 % of all the materials introduced to the global market came from reused or recycled materials (Stena Recycling, 2021). This means that over 90 % came from virgin materials, which indicates that the global economy is still very linear. The two significant issues with the linear economy are that the resources will run out eventually, and it will create a big pile of waste in the end, which can be harmful to both humans and nature. Resources are lost through the linear economy. Another shortcoming of a linear economy is that economic values are lost simultaneously, which could have been recovered and turned into an opportunity (Stena Recycling, 2021).

Design for Recycling is a design approach that ensures products recyclability. According to Bakker, C et al. (2016), the primary strategies for Design for Recycling is *Disassembly, Design for a Technological Cycle*, and *Design for Biological Cycle*, further explained in table 5, which also links to the recycling definitions in table 6:

Table 5. Design for Recycling Strategies (Bakker, Bocken, de Pauw, & van der Grinten, 2016)

DESIGN FOR RECYCLING STRATEGIES	
Disassembly	The product should be possible to take apart to different recycling categories. It is imperative to separate technical and biological (Bakker, Bocken, de Pauw, & van der Grinten, 2016).
Design for a technological cycle	The materials should be possible to recycle and/or recover into materials that have comparable properties as the original (primary and tertiary recycling, as referred to in table 6 on the following page) (Bakker, Bocken, de Pauw, & van der Grinten, 2016). McDonough and Braungart push the approach a bit further to state that the quality of the material should be preserved (Eppinger & Ulrich, 2012). They also clarify the difference between "upcycling" and "downcycling." Downcycled materials are considered to have a lower value and may never accomplish circular flows. It will only delay the linear process from product to waste and eventually end up in *quaternary recycling* or *thermal recycling,* described in table 6, which is not desirable from a circular point of view.
Design for a biological cycle	This approach is suitable for consumer products. The material must be possible to return to nature, which means it should contain safe and healthy materials (biological nutrients). The products should be biodegradable, creating fertilizer and food for the biological system when it returns to nature. Materials break down in different ways in nature, such as fungi, microorganisms, and bacteria. Composting can be referred to as tertiary recycling in table 6.

Table 6. Recycling definitions based on plastic recycling terminology, adapted from (Bakker, Bocken, de Pauw, & van der Grinten, 2016).

RECYCLING METHOD	DEFINITION
Primary recycling, also referred to as closed-loop recycling.	Mechanical reprocessing into a product with comparable properties. "Upcycling" is concerned with retaining or improving the properties of the material.
Secondary recycling, also referred to as downgrading or downcycling	Mechanical reprocessing into products requiring lower properties. In secondary recycling, the material is reprocessed into a "low" value product.
Tertiary recycling, also described as chemical or feedstock recycling (depolymerization & re-polymerization).	Recovery of the chemical constituents of a material. More extensively defined as the structural breakdown of materials into their original raw core components with properties equivalent to the original material.
Quaternary recycling, also described as thermal recycling, energy recovery, and energy from waste.	Recovery of energy from materials. Within a circular economy, this category is not considered recycling.

When designing for recycling the material selection is essential. It is important that the material does not harm humans, animals, and nature. McDonugh and Brungarts argue (Braungart & McDonough, 2019):

> – *"designing products that are merely less harmful to the environment due to incremental improvements such as reduced energy use, waste generation, or use of toxic materials is not sufficient because such products are still unhealthy for the environment"*.

Although a specific material is considered recyclable in theory, it will not always be recycled (Stena Recycling, 2021). Stena Recycling is a recycling company operating in Sweden and the Nordic countries. They have presented requirements to accomplish circular design and facilitate recycling shown in figure 6 and further explained in the following list.

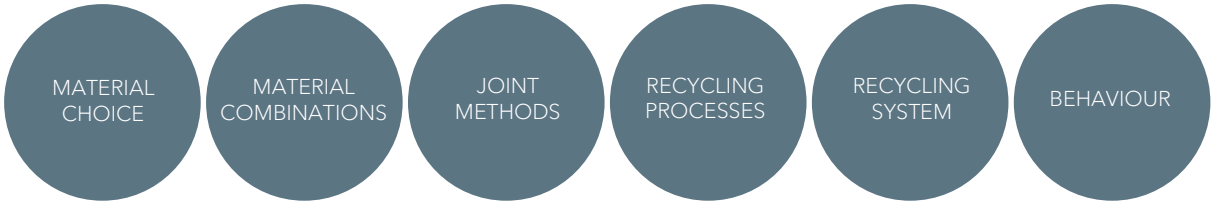


Figure 6. Circular Design, adapted from (Stena Recycling, 2021).

- **Material Choice** - The material should be recyclable in theory, and there should be a demand for the recycled version of the material (Stena Recycling, 2021).
- **Material Combinations** - Some materials can contaminate each other if they are not separated in the sorting process, resulting in decreased quality of the recycled material (Stena Recycling, 2021).
- **Joint Methods** - The joint affects the possibilities of separating materials from each other. Plastics with glue and 2K molds are challenging to separate (Stena Recycling, 2021).
- **Recycling Processes** - There should be an available recycling process on a sufficiently large scale. Bioplastics are not recycled at the time of writing, for example, since there is no conventional collection system and no adapted recycling process (Stena Recycling, 2021).
- **Recycling System** - There should be a system for the material at its end of life, including collection, recycling systems, and a demand for the recycled version in the specific stream. PET bottles, for example, have a particular collection system that works highly efficiently where new bottles are produced out of reused materials. But if PET is used in an office chair, it is not entirely sure the PET will be recovered since the chair belongs to a different recycling stream that doesn't handle PET (Stena Recycling, 2021).
- **Behavior** - Knowledge, time, and effort put into the problematization are essential to the output.
- **Design for Reuse** - Design for Reuse is a design approach that ensures that products can be reused. This is considered an essential part of a circular economy. The reuse approach slightly differ from the recycling approach, see figure 7 (Stena Recycling, 2021). But the approach is nevertheless essential to consider in the overall design.

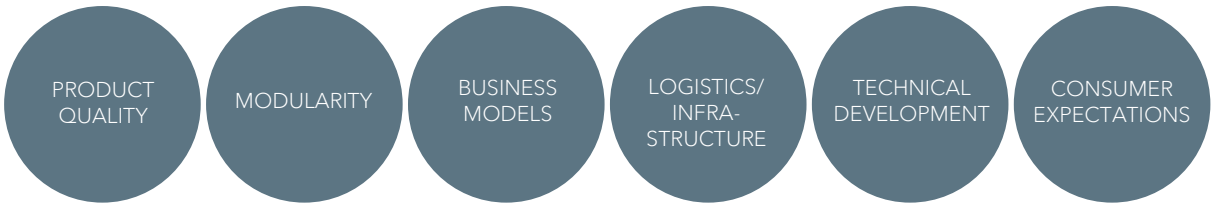


Figure 7. Design for reuse, adapted from (Stena Recycling, 2021).

2.4 When to Adapt the Methods

There are various processes to adapt for product development projects. Most follow similar paths with some variations. Some process examples are *Engineering Design: a systematic approach* (Beitz, Feldhusen, Grote, & Pahl, 2007), and IDEO's *Design Thinking* (IDEO, 2021). Another process is the product development process (PD process) established by Ulrich, K.T. & Eppingers, S.D. (2012). The PD process is outlined with steps to follow in figure 8. A reflection should be conducted after each step in the PD process to ensure the credibility of the results.

Figure 8. – The product development process according to (Eppinger & Ulrich, 2012).

Regardless of the development processes used, it is essential to integrate circular strategies from the beginning to ensure sustainable product results (Eppinger & Ulrich, 2012). It is also more resource-efficient because eventual changes in the later stages of the process often become more expensive and time-consuming if even possible to implement (Eppinger & Ulrich, 2012). The strategies should therefore be integrated already in the planning and concept development phases. It should also be integrated and continue throughout the development process rather than used as a complementary strategy. Eppinger and Ulrich (2012) suggest using DfE (Design for Environment) throughout the development process, see figure 9.

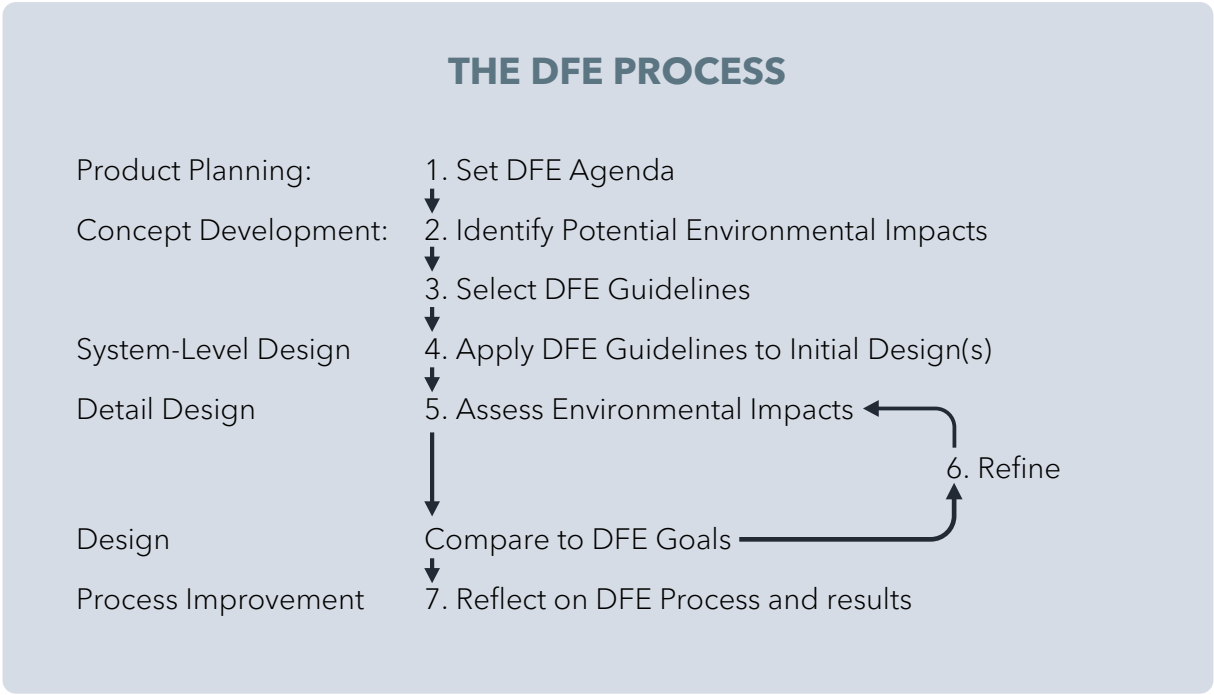


Figure 9. The DfE process (Eppinger & Ulrich, 2012).

3

METHOD

This chapter covers the various method that was used to conduct the thesis. It describes how the work have been conducted in order to reach the thesis objectives.

The thesis process is based on the double diamond design process, earlier presented in figure 1 (IDEO, 2021). The process is derived into two phases. The first phase(explore and analyze) investigates the current situation and the second phase(create and test) summarizes the compiled information into design guidelines to be tested and evaluated by second sources. Information gathering has been a significant part of the thesis process, and the search is based on life cycle thinking which integrates with the circular design theory presented in chapter 2. The whole work process is represented in figure 10, and each method is further described in the respective subchapter that follows.

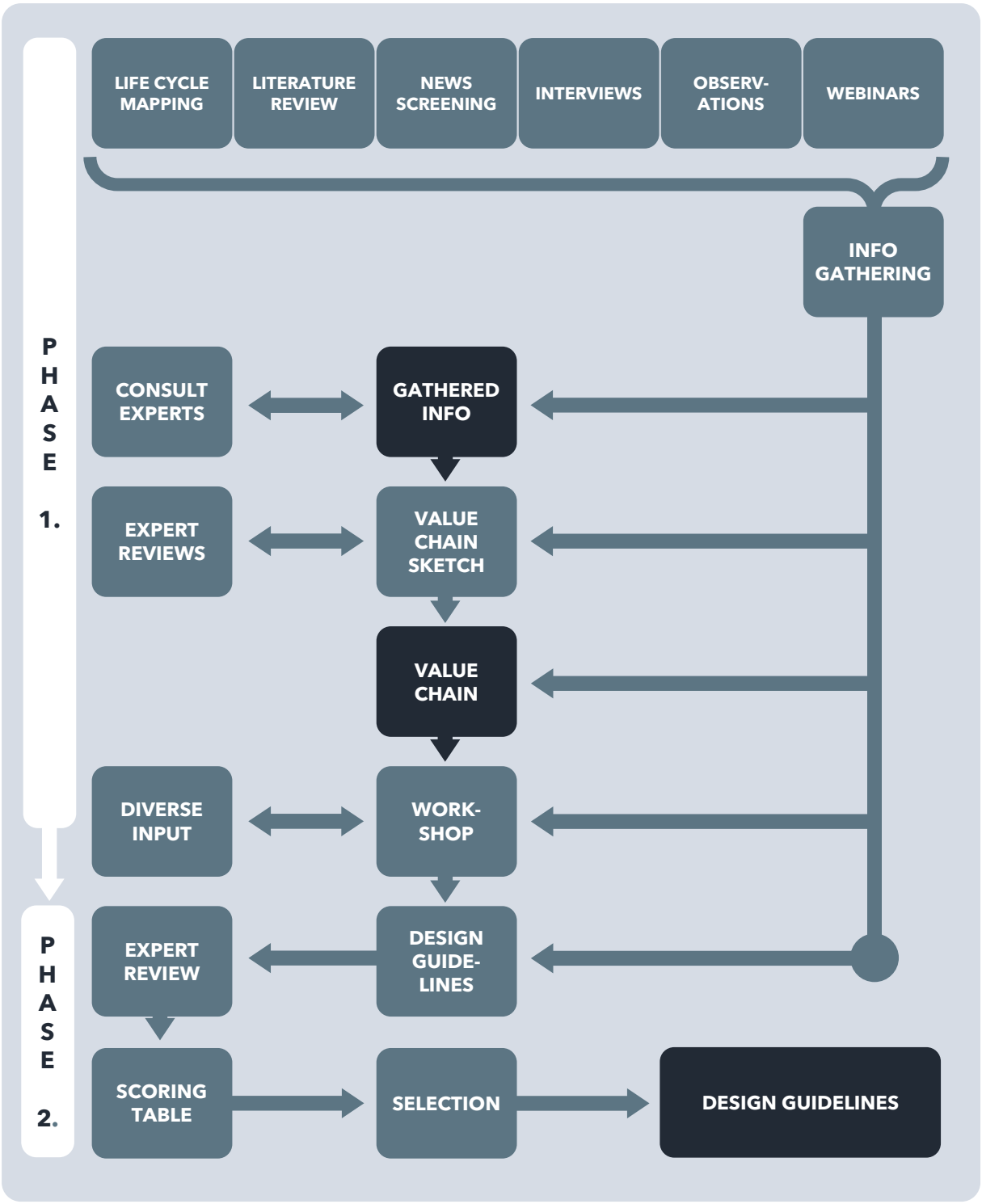


Figure 10. Conducted thesis process.

3.1 Information Gathering

The purpose of searching information is to obtain knowledge and understanding of the subject and the problems (Eppinger & Ulrich, 2012). The information search was conducted using different methods such as literature reviews, news screening, interviews, observations, and attending digital webinars and lectures. The information search results can mainly be studied in chapter 4, which creates a fundamental base that further results in the value chain in chapter 5 and the design guidelines in chapter 6. The information-gathering focused primarily on:

- Mapping the value chain
- Legislation
- Li-Ion chemistries, materials, and shapes
- Recycling strategies of li-ion batteries and relating products

An external search is a process for collecting information (Eppinger & Ulrich, 2012). Such investigation aims to identify solutions to the problem by enlarging the studied scope by investigating information related to the addressed problem. Then the more promising directions are studied further. An external search can be conducted through interviews with top users, consultation with experts, patent search, literature search, and benchmarking. Some of the mentioned methods have been used through the thesis project and are described in the following subchapters.

3.1.1 Life Cycle Mapping

Life cycle thinking is part of circular design and business models (Eppinger & Ulrich, 2012). The life cycle of a product may be mapped out to give a more holistic perspective of the value chain and the phases a product might pass (University of Cambridge, 2021). The first step of the method is to conduct a so-called life cycle inventory (LCI) where a system model is built up (Baumann & Tillman, 2004). The system model is a flowchart of a technical systems pathway from "cradle-to-grave" (preferably "cradle-to-cradle"). It commonly addresses the system activities such as production, processes, transport, usage, and waste management (Baumann & Tillman, 2004). The life cycle is mapped to provide an overall understanding and reduce the risk of sub-optimization. Sub-optimization could be to design solutions that aggravate the conditions at some other stage. The life cycle formed the area of investigation from where different tracks were investigated throughout the thesis. The mapping resulted in the value chain image in chapter 5, figure 39.

3.1.2 Literature Review

A literature review aims to identify and obtain knowledge (Eppinger & Ulrich, 2012). A literature study was conducted using several databases, search engines, and books available through the Chalmers University of Technology library. Other tools used were search engines like Google Scholar and databases like ScienceDirect, iva, and ResearchGate. In cases, the literature studied was peer-reviewed (marked with peer-reviewed in databases), which indicates objectivity and a maintaining scientific standard. The literature study was a central part that was necessary to carry out the thesis.

3.1.3 News's Screening

An adopted external search was conducted by screening newsfeeds in related forums like omEV's Newsletter, the newspaper NyTeknik, and li-ion battery-related actors and people on LinkedIn (Eppinger & Ulrich, 2012). Examples of the latter are actors like the Swedish Energy Agency, Vinnova, ivl, Northvolt, Hydro, Batteries News, Stena Recycling, and professionals/experts within the field. A screening of news on LinkedIn was conducted nearly daily and resulted in receiving information about upcoming events and further research to investigate. The lithium-ion battery industry is moving fast, and LinkedIn gave access to up-to-date information. The lithium-ion sector is still young, constantly evolving why this approach created knowledge in the current situation.

3.1.4 Interviews

Experts and actors within the field have been contacted and interviewed to gather fundamental and up-to-date knowledge. The contacts have mainly been performed digitally due to the restrictions of the Covid-19 pandemic at the time of writing, whit a few exceptions. Communication has taken place through email, telephone calls, digital video meetings, and face-to-face interviews. The experts contacted are mainly active in the lithium-ion battery field, such as researchers, recycling actors, and manufacturers. The interviews have been semi-structured and unstructured (Ericson, Wikberg Nilsson, & Törlind, 2015).

In addition to the interviews, more spontaneous telephone conversations have also been an important part. Sometimes these calls led to instant feedback pointing towards a

particular direction to be further investigated. It has been a source of specific content, and the conversations gave valuable guidance.

3.1.5 Attending Digital Webinars

Another adopted part of the external search was made by attending different webinars, digital conferences, and lectures (Eppinger & Ulrich, 2012). The materials were accessed through live broadcasts and recorded materials, giving access to valuable and trustworthy information from reliable sources. It has also created a broader perspective and added knowledge of the current situation. The essential webinars are listed in Appendix IV.

3.1.6 Observations

Observations are a way to understand events (Ericson, Wikberg Nilsson, & Törlind, 2015). Due to the situation of Covid-19, traveling was restricted at the time of conducting the thesis. Therefore, observations were mainly performed digitally through online content such as YouTube videos, except a study visit at Stena Nordic Recycling Center in Halmstad, Sweden, March 2021. Some observations are stated below and include various subjects such as battery teardown videos and recycling:

Study Visit at SNRC - Stena Nordic Recycling Center, Halmstad Sweden
A study visit was made at Stena Nordic Recycling Center (SNRC) in Halmstad, Sweden, led by Tom Leppäjoki, March 2021. The tour showed electric waste recycling, plastics recycling, and the battery recycling facility.

Observation - LIBs Recycling - Volkswagen Facility
An observation was made to study manual disassembly and automated recycling of a lithium-ion battery from an EV (electric vehicle) at Volkswagens facilities in Germany. The observation showed the recycling step by step, which is mapped out in Appendix V (YOUCAR, 2021). Video: https://www.youtube.com/watch?v=b7gcnlrlQSU

Observation - Robot Disassembly
Automated disassembly of EV batteries with robots was observed through a YouTube video by Circular Energy Storage (Melin, 2020).
Video: https://www.youtube.com/watch?v=OyR0XdZbMx0

Observation – Tesla Battery Teardown
Munro Live conducts a battery teardown of a Tesla Model Y battery, which was observed through their YouTube channel. However, this is a hazardous approach and should not be performed by untrained personnel (Munro Live, 2020).
Video: https://www.youtube.com/watch?v=4JiDZVO9NdM&t=4s

Observation - KYBURZ LIBs Disassembly
KUBYRZ has developed a sustainable battery concept that makes it possible to disassemble the battery cells (KYBURZ Switzerland AG, 2021) (Melin, 2021b).
Video: https://www.youtube.com/watch?v=Yr0MP25nBtI&t=372s

3.2 Sketching and Visualization

Sketching and visualization are strategies worshiped by Shaw (2015), who claims it is easier to process and remember information through images compared to texts. Sketching was used to visualize the value chain in pictures rather than by text, and this approach formed the basis for communication during interviews and reviews. Sketches were shared, refined, and adjusted iteratively during the interviews. It resulted in instant feedback, and the interviewees contributed with insightful stories and pointing out possible shortcomings in the value chain pathway. The visualization of the value chain thus constituted a tool for ideation and empathizing. The sketches were initially performed on a quick and dirty basis with pen and paper and post-it notes. The illustrations were refined into symbols and resulted in, among other things, the value chain image in figure 39, chapter 5. Visualization also constitutes the method used to present parts of the thesis results in the report.

3.3 Evaluation

Evaluations can be performed to validate the findings (Eppinger & Ulrich, 2012). Evaluations were iteratively performed throughout the thesis process through several reviews and interviews where the interviewee has reviewed the value chain flowchart. The workshop in the following chapter may also be considered as part of the evaluation where different professionals had their say on the presented materials.

3.4 Workshop

A workshop is a strategy to collect ideas during a limited period (Ericson, Wikberg Nilsson, & Törlind, 2015). A workshop was held with 24 people from Micropower Sweden AB by including different professions such as management, sustainability, business development, software engineers, hardware engineers, mechanical engineers, test engineers, and project leaders. The workshop was held digitally through Microsoft Teams. The workshop was

initiated with a short presentation about lithium-ion battery recycling strategies and the value chain steps together with their shortcomings. The presentation was followed by a digital workshop using the digital tool Miro (accessed through miro.com), where the participants got access to the Miro-wall illustrated in figure 11.

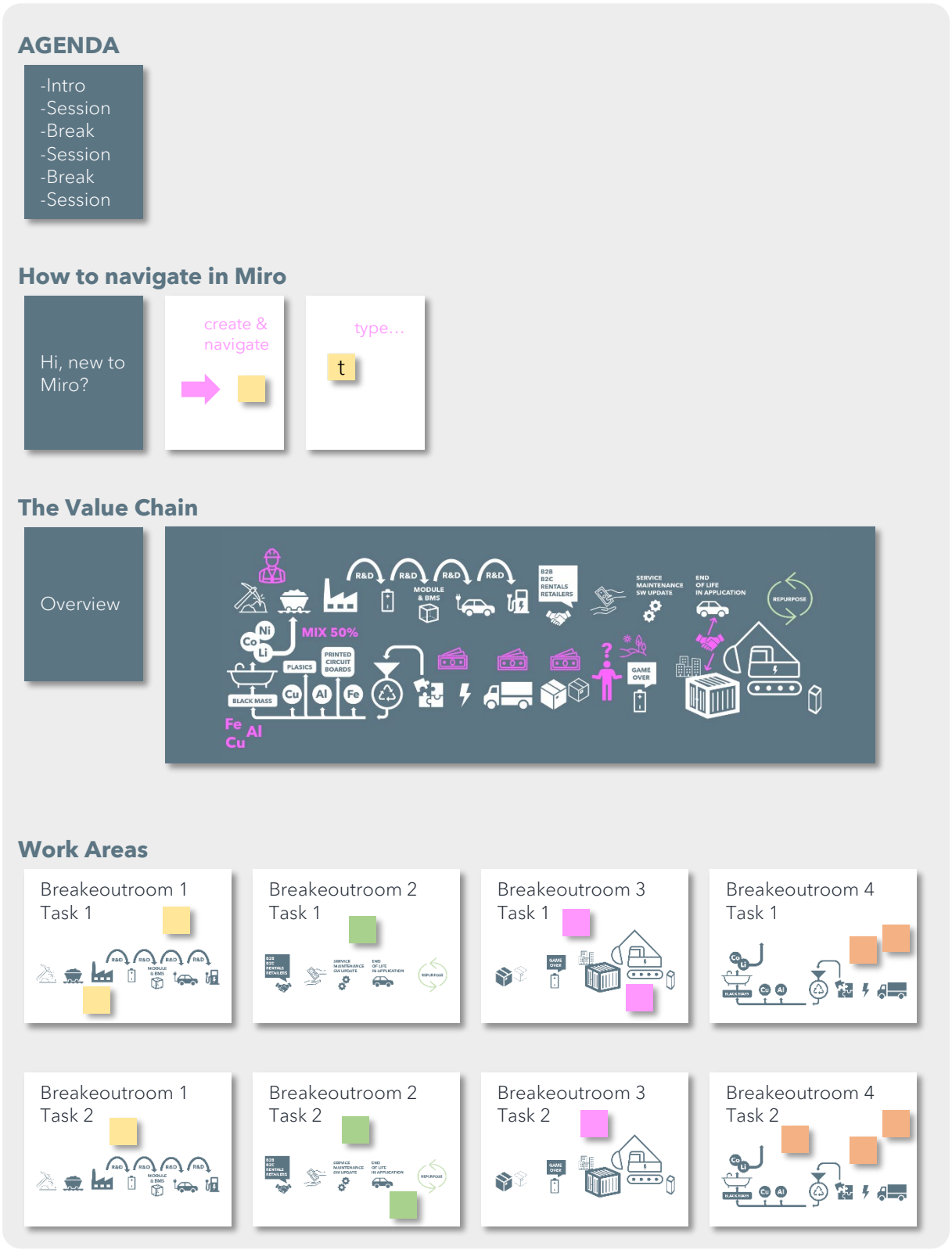


Figure 11. Miro tool and dedicated working areas.

The participants were divided into breakout rooms with 3-4 people, and each group was addressed to a dedicated working area on the Miro-wall. While in the breakout rooms, the groups were asked to find answers to questions regarding the battery Value Chain through group work. Each group focused on a limited part of the value chain. The workshop was conducted through two sessions, given 20 minutes each with breaks in-between. During the first session, they were asked to answer "*1. Find issues and threats hindering a closed loop of the value chain?*" During the second session, they were asked, "*2. Find solutions to close the loop?"*. The answers were collected on digital post-it notes in Miro. After each session, each group presented their three most important findings through a so-called "3 minute-elevator-pitch". The workshop resulted in various ideas that were brought further through the process.

3.4.1 Information Gathering Output

The information-gathering contributed to the three results:

.

1. **Compiled information represented in chapter 4:**
   The compiled information covers general information about lithium-ion batteries, legislation, recycling of electronic waste and recycling, and lithium-ion batteries. This information was used to empathize, among other things, with the possible challenges of the battery pack constructions

2. **The value chain roadmap represented in chapter 5:**
   - The value chain roadmap gave further input to the possible events and people crossing the product throughout its lifetime.

3. **Design guidelines represented in chapter 6:**
   - The information-gathering found various incentives for recycling, especially when combined with the fundamental circular theories in chapter 2. The search also discovered previous research and stated design guidelines that correlated with the thesis topic of circularity. The USCAR (UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH LLC) provides a list of design guidelines collected in the report called "Recommended Practice for Recycling of xEV Electrochemical Energy Storage Systems" created by BRWG (The Battery Recycling Work Group) (BRWG, 2014). This list mainly focuses on energy storage systems but was found suitable for the thesis topic as well. Amnesty International also states a shorter list of design guidelines in its "Powering Change" report from 2021 (Amnesty, 2021).

   These external guidelines list actions but generally do not explain why the measures are essential, though it is possible to interpret as a reader. However, the thesis information gathering has gathered incentives that match with the guidelines and substantiate their relevance. The external design guidelines have been used, adopted, and further developed throughout the thesis. These external design guidelines thus contribute to parts of the thesis's final design guidelines.

3.5 Focused Evaluation and Analysis 1

An adopted KJ-analysis was conducted to sort all the gathered information compiled during the thesis work (Bligård, 2015). The data was moved around digitally in a text document to be organized into themes with similar statements. Eventually, the findings from the compiled information and the outlined value chain constituted a summarized view of more or less relevant aspects to consider to design recyclable lithium-ion battery packs. The aspects were gathered in a list that was selectively reduced to only cover lithium-ion-specific aspects. The list was then converted into 37 stated design guidelines, including arguments of why they should be considered in the design stage. The guidelines were placed in a questionary, and a cut out from the questionnaire is represented in Figure 12.

HOW RELEVANT ARE THE DESIGN FACTORS?									
No.	Design Factor	Description	1=least, 5=most, N/A=Not Applicable						
			1	2	3	4	5	N/A	Optional Comment:
1.0	**GENERAL**								
1.1	Know Why & How	•Knowledge of incentives (Why), and strategies (How), in order to make DfR happen. •Leaders to substantiate work. •Purchase/R&D as setting the level.	☐	☐	☐	☐	☐	☐	Click or tap here to enter text.

Figure 12. A cut out from the Scoring Table.

A questionnaire is a method to receive selected people's insights, for example, from possible users (Bligård, 2015). In this case, the targeted people of interest were experts within the lithium-ion industry, with the aim to state the legitimacy of each design guideline based on their knowledge and expertise. Therefore, the questionnaire was sent out digitally to be evaluated by a small number of selected people within the Swedish lithium-ion battery industry. The questionnaire was produced in Microsoft Word in such a way it enabled limited access for the participants to make changes. The scoring table started with a text that introduced the reader to the topic and the problematization. Then it requested the reader to state each design guide's relevance on a scale of 1-5 or Not Applicable (N/A), where 1 had the slightest bearing, and 5 had the greatest. The participants were also able to add a comment if they desired. The whole scoring table can be seen in Appendix VI, including the average answer for each question based on answers from 10 individuals. A more detailed list of the responses may be found in Appendix VII.

3.6 Focused Evaluation 2

Follow-up contacts were held with each individual respondent of the questionnaire. Either via email, phone, or zoom meeting depending on the respondents' availability. The follow-up contact consisted of semi-structured interviews to ensure that the participants understood the issues of the questionnaire. The discussions also aimed to give further feedback and insight into how the participants had perceived the survey queries (Bligård, 2015). The verbal data from the follow-up sessions were combined with the survey data(the scoring output) to select and refine the final design guidelines. The design guidelines resulted in four main approaches that summarize the most crucial aspects of recycling lithium-ion battery packs in chapter 6.1. The analysis also resulted in a more comprehensive list of design guidelines is more detailed. The extensive list may be seen in chapter 6.2.

3.7 Personas

A persona is a description of a fictive person that symbolizes people from the target group (Ericson, Wikberg Nilsson, & Törlind, 2015). The definition of a persona is built upon collected information about the target group, such as statistics, interviews, observations, etc. The aim of personas is to create empathy for the users and their needs in order to design suitable solutions. In this case, the project does not develop a product or a service but instead establishes design guidelines. However, the thesis collects a more considerable amount of data that has given insights into possible scenarios with people that may occur during the value chain. Personas are therefore used in an adopted way to create empathy for these eventual scenarios of the value chain, described in chapter 5.

3.8 Storytelling

Chapter 5 present the value chain pathway through a narrative approach and adapt a method called storytelling. Storytelling is a way to distribute information through stories (Maer, 2016). A story can catch the reader's attention more efficiently and intensively and is more motivating than data statistics and figures. Stories create emotional connections between the perceiver and the story's content, and when people are emotionally attached, they are far more likely to take action (Maer, 2016). Storytelling is therefore used to create empathy with the value chain path and its involved people. The lithium-ion battery value chain actors are sometimes located far from each other, both business-wise and physically. The story, therefore, aims to create bridges of empathy between the actors and decision-makers within the value chain.

4

COMPILATION OF INFORMATION GATHERING

Gathering information has been a significant part of the conducted work throughout the thesis and can thus be seen as part of the thesis result. This information compiled creates an overall problem understanding. The chapters may be read individually and selectively reliant on the expertise of the reader. The chapter includes section 4.*1 Lithium-ion Batteries, 4.2 Legislation, 4.2 Recycling Electronic Waste,* and *4.3 Recycling Lithium-ion Batteries*. It has been essential to empathize with the circumstances to map the value chain and create the design guidelines described in chapter *5 Result*.

4.1 Li-ion Batteries	Information of lithium-ion batteries covering physical types, applications, chemistries, safety, characteristics, serial- and parallel connections, balancing, and BMS functionality.
4.2 Legislation	An outlook of laws and regulations covering li-ion batteries from vehicle applications on the European market. Besides the EU Battery Directive, the brought-up legislation also addresses product design, waste, transportation, and handling. Finally, a brief outlook of legislation worldwide is given.
4.3 Recycling Electronic Waste	Lithium-ion batteries are highly integrated with electronics that monitor and adjust the cells during their operation, why electronic waste recycling is closely linked. The recycling strategies for electronic waste also bring value to the scope as they are similar to those of Battery Recycling.
4.4 Li-ion Battery Recycling	Sum up the most common recycling strategies for lithium-ion battery recycling today, a comparison between them, active actors on the European market, and collection systems.
4.5 Li-ion in the Future	The chapter is summed up by an outlook of lithium-ion batteries.

4.1 Lithium-Ion Batteries

A battery stores energy for future use. The battery cell consists of a positive electrode called a cathode and a negative electrode called the anode, see figure 13 (Tomsic, 2019). The cathode is often a metal oxide that can take up the lithium ions, and the anode is often graphite with embedded lithium. Between the anode and cathode is a separating thin perforated layer of a polymer material. This whole setup sits in a liquid electrolyte, regularly organic. The electrolyte conducts lithium ions but does not conduct electrons, i.e., it does not conduct electric current. The perforated layer and the electrolyte enable the lithium ions to travel from the cathode to the anode and vice versa. When the ion moves, energy can be extracted.

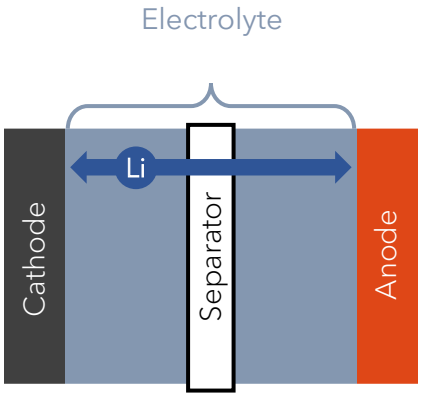


Figure 13. Cathode, separator, anode, electrolyte (Tomsic, 2019).

Lithium is the lightest metal of all, and thanks to its characteristics, it can offer a very high energy density per weight unit (Battery University, 2021). Lithium-ion batteries are an umbrella concept covering many different cell types and chemistries (Batteriföreningen, 2019). The most significant advantage of lithium-ion technology is the high energy density, which varies depending on both the cell type and the cell chemistry.

4.1.1 Cell Types

The most common li-ion battery cell types are presented in figures 14 and 15. These are known as cylindrical-, prismatic- and pouch cells (Schönemann, 2017). The types can have different construction, which gives unique characteristics as well as price pictures.

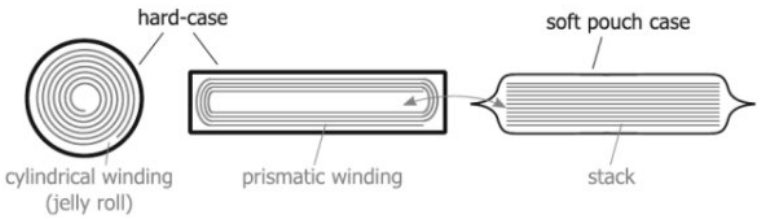


Figure 14. Cross-section of types of electrode-separator package and cell housing (Schönemann, 2017). (Courtesy of Malte Schönemann, 2021).

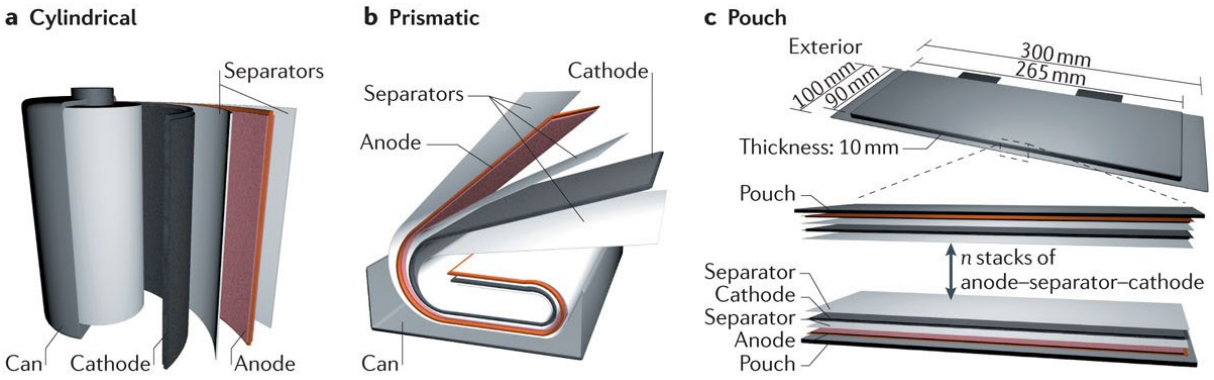


Figure 15. Different LIB cell types (Aurbach & Choi, 2016).
(Courtesy of Doron Aurbach, 2021, Bar-Ilan University)
Promise and reality of post-lithium-ion batteries with high energy densities
Nat. Rev. Mater. doi:10.1038/natrevmats.2016.13

Cylindrical cells
Cylindrical cells are built up by long strips of metal foil coated with electrode material on both sides (Batteriföreningen, 2019). The electrodes are rolled up with a separating porous polymer into a so-called "jelly-roll." The roll is placed in a cylindrical-shaped casing of stainless steel that creates the cell can.

Prismatic cells
The prismatic cells are built up using either of two different strategies (Batteriföreningen, 2019). Either the strips and separators are winded/folded into a cylindrical shape, or two-sided coated sheets are stacked every other anode and cathode with a separator in between. The cell can is often made of aluminum.

Pouch cells
The most significant difference with pouch cells is that they lack a hard case outer can, and instead, they can consist of a thin laminated aluminum foil (Batteriföreningen, 2019). This softer can makes the cells more vulnerable to shocks. They are also more sensitive to swelling when heat built up as the batteries are charged and discharged. Therefore these cells are often put into a plastic case that holds together the cell structure to prevent it from swelling and protect it against external shocks.

4.1.2 Application

A single battery cell can be referred to as a battery (Edström, 2021). Battery cells connected into a battery module can also be referred to as a battery. Connected battery modules in an energy storage system can also be referred to as a battery. The terminology can thus be confusing. In order to create clarity, the following language will follow Schönemanns structure presented in figure 16 (Schönemann, 2017). Schöneman divides the structure into levels of cells, modules, and systems.

A BMS (Battery Management System) controls the battery system and contains electronics such as circuit boards, cables, and software, etc. (Harper, et al., 2019). A thermal management system and a cooling plate can be used to keep the system at the desired temperature.

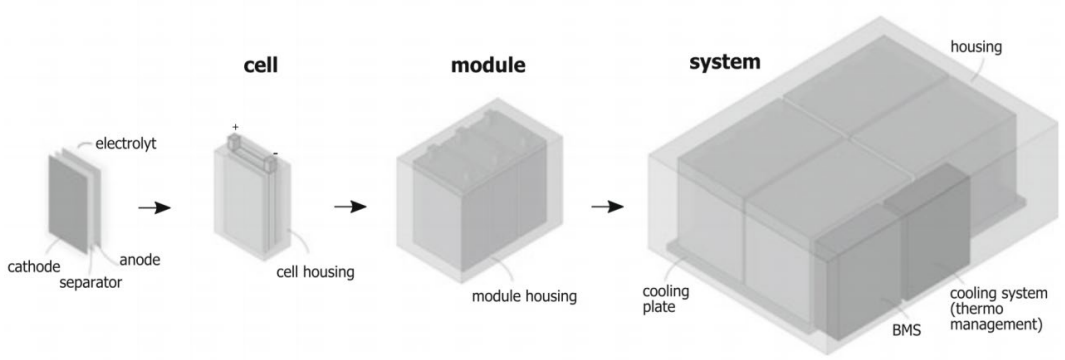


Figure 16. Battey system components (Schönemann, 2017).
(Courtesy of Malte Schönemann, 2021).

Battery systems are further mounted in an application, for example, an EV (Electric Vehicle). The systems are often highly integrated with the application (Sundström, 2020). These units usually require robust solutions to withstand the external stresses and challenges that the application is expected to face. Until today glue has been a commonly used fastening method throughout the systems, and manufacturers have made it difficult to reach the battery modules and the cells (Edström, 2021).

4.1.3 Cell Chemistries and Materials

Different battery cell chemistries contain different materials where both the cathode and anode content may differ. The battery chemistry is commonly addressed by the cathode content, as is the case for the most common li-ion battery chemistries known as NMC, LFP, LCO, NCA, and LMO (Zackrisson, 2017). These are all cathode materials and are commonly used with graphite anodes. The cathode content is further stated below:

NCA	Lithium-nickel-cobalt-aluminum oxide (LiNiCoAlO2)
NMC	Lithium-nickel-manganese-cobalt oxide (LiNiMnCoO2)
LCO	Lithium-cobalt oxide (LiCoO2)
LFP	Lithium-iron phosphate (LiFePo)
LMO	Lithium-manganese oxide (LiMn2O4)

The most valuable materials in the battery cells are cobalt, copper, nickel, manganese, aluminum, and lithium (Ekberg & Petranikova, Chapter 7 - Lithium Batteries Recycling, 2015). The cathode material is often referred to as the black mass and includes cobalt, nickel, manganese, and lithium. Where cobalt is the most valuable material (Melin, 2019). Detailed materials content per cell chemistry can be found in table 7 on the next page, adapted from (Melin, 2019). The material prices are affected by prevailing supply and raw material prices, which vary over time. At the time of writing, both LFP and LMO are considered to have low material values (Kushnir, 2015).

More information about cell characteristics may be found in Appendixes. Different chemistries have individual properties mapped out in Appendix I (Saldaña, Ignacio San Martín, Zamora, Javier Asensio, & Oñederra, 2019). The characteristics make the batteries more or less suitable for various applications, examples may be found in Appendix II

(Saldaña, Ignacio San Martín, Zamora, Javier Asensio, & Oñederra, 2019). Each chemistry's advantages and disadvantages are mapped in Appendix III, adapted from (Kushnir, 2015).

Table 7. Material content per cell chemistry, adapted from (Melin, 2019).

MATERIAL CONTENT, % in a cylindrical cell (18650)						
Material	**NCM111**	**NCM811**	**NCA**	**LFP**	**LMO**	**LCO**
Casing						
Steel	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%
Aluminium	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%
Current collectors						
Aluminium	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%
Copper	7,0%	7,0%	7,0%	7,0%	7,0%	7,0%
Anode material						
Graphite	18,1%	18,1%	18,1%	18,1%	18,1%	18,1%
Cathode material						
Manganese	6,1%	1,8%			19,4%	
Lithium	2,3%	1,9%	2,3%	1,4%	1,2%	2,3%
Cobalt	6,5%	1,9%	2,9%			19,3%
Nickel	6,5%	15,4%	15,6%			
Aluminum			0,4%			
Iron				11,3%		

The demand for the different chemistries is expected to vary over time, according to the estimation in figure 17 (Zackrisson, 2017). The materials relate to different aspects of sustainability, such as nature, social and economic aspects.

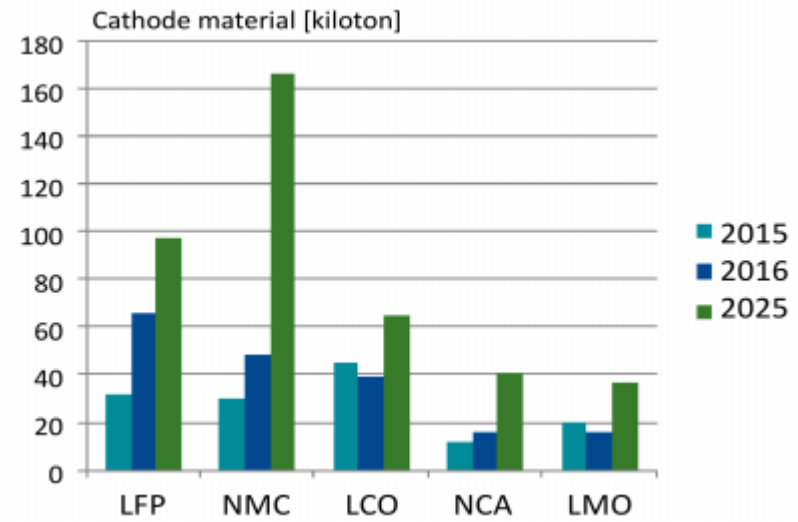
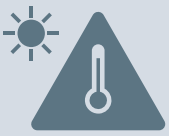


Figure17. Forecast of the dominating LIBs chemistries per year (Zackrisson, 2017). (Courtesy by Mats Zackrisson, 2021, RISE).

4.1.4 Safety Outlook

Lithium-ion batteries are safe when handled correctly (Tomsic, 2019). However, some conditions pose safety risks. The following table 8 gives an overview of the risks.

Table 8. Hazardous risks with lithium-ion batteries, adapted from (Karlsson & Lindström, 2018) (Battery University, 2021) (Tomsic, 2019) (BIL Sweden, 2011).

CATEGORY	RISK/HAZARD
 ELECTRICAL	• Electric chock • Short Circuit • Arc – an arc of current passing through the air is extremely hot and powerful, risking burns and ignition of nearby flammable materials. It may occur during a short circuit.
 COLD TEMPERATURES	< 0 °C • May cause an inner short circuit if charged below 0 °C because of dendrite crystals built up.
 WARM TEMPERATURES	>60 °C approximately (depending on battery chemistry etc.) • Cell chemistries start to change. • Abuse, internal or external, may lead to thermal runaway leading to fire/explosion.
 FIRE	• Flammable components and reaction products • Self generates oxygen during thermal runway=difficult to extinguish fires (does not apply to the LFP cell chemistry). • Leakage • Contamination
 EXPLOSION	• Pressure • Leakage • Contamination
 CHEMICAL	• Carcinogenic coating materials. • Toxic gases.

4.1.5 General Characteristics

Lithium-ion batteries cannot be fully charged or discharged to their outer limits (Tomsic, 2019). It is possible to say that the batteries have a so-called performance window that is set by mechanical(depending on molecular kinetics) and electrochemical constraints that depend on respectively cell temperature and cell voltage, which is represented in figure 18. Battery and cell suppliers often specify cycle life within certain conditions based on allowed current for charge and discharge, cell voltage, and temperature, which create the performance window (Tomsic, 2019).

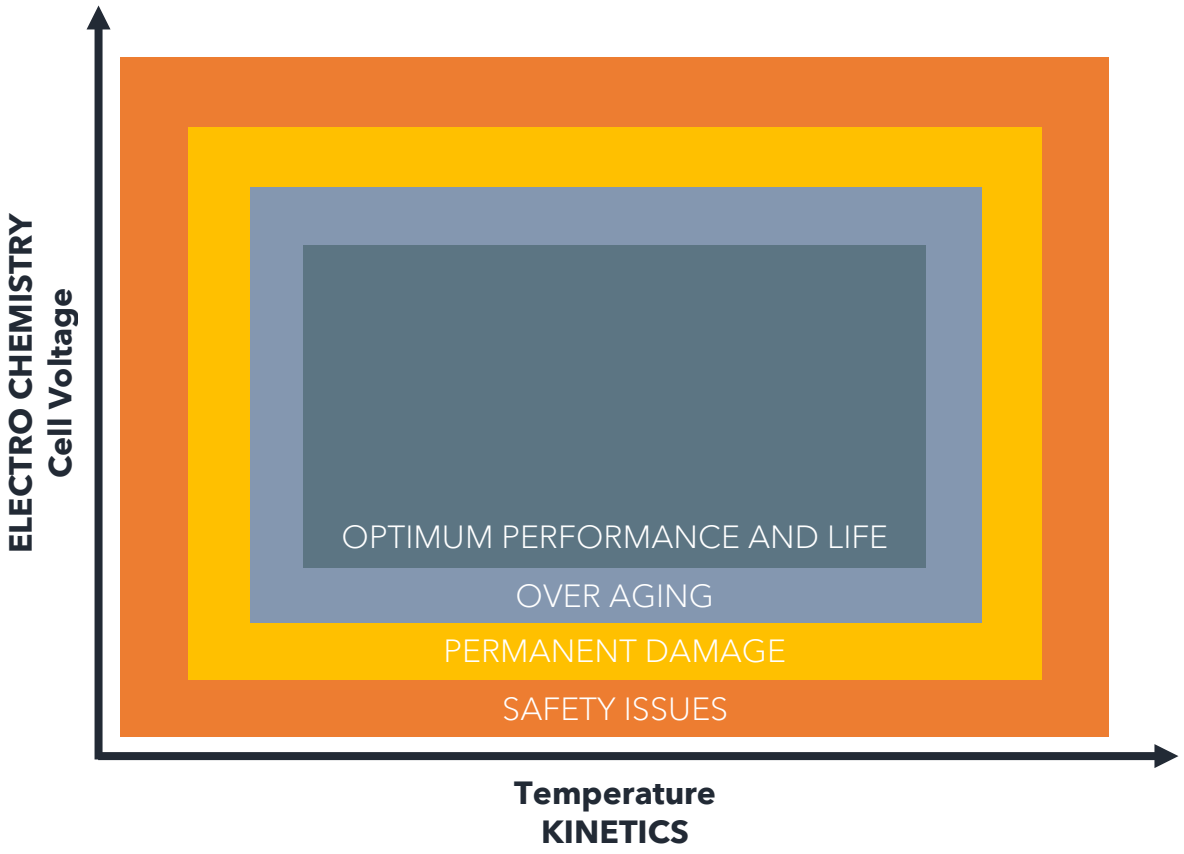


Figure 18. Li-Ion battery performance window (Tomsic, 2019).

All batteries also age over time, whether used or not, due to material degrading that reduces capacity (Tomsic, 2019). The status of the batteries in this regard is described as SoH (State of Health). Batteries age faster if used outside their performance window limits. According to figure 18 there are also limits where *permanent damage* and *safety issues* occur. During these events, reactions begin inside the batteries that cause irreversible changes. The *safety issue* area is the most critical, and its reactions are listed below for high and low voltage as well as high and low temperature (Tomsic, 2019).

High voltage within the safety issue area include (Tomsic, 2019):

- Electro chemical breakdown of the active materials.
- Gas evaporation.
- Electrochemical breakdown of the electrolyte.

Low voltage in the safety issue area include (Tomsic, 2019):

- Electro chemical breakdown of the solid electrolyte interphase layer (SEI). This layer is a formation on the anode's surface and has a vital role in lithium-ion batteries' cyclability over time.
- The copper in the anode's current collector may be dissolved.
- A dendritic formation can lead to an internal short circuit.

High temperature in the safety issue area includes (Tomsic, 2019):

- Thermal side reactions.
- Thermal degradation of the SEI.
- The separator shrinks/melts.
- Thermal decomposition of the electrolyte.
- Gas evolution.
- Thermal decomposition of electrode/active materials.

Low temperature in the safety issue area include (Tomsic, 2019):

- Li-plating.
- Increased impedance (the ions move slower)
- Ion conduit

Batteries have a level of self-discharge which means they get discharged over time if they are not used. A deeply discharged battery, for whatever reason, should never be recharged and used again due to safety reasons (Tomsic, 2019). The same applies to overcharged batteries. Overcharged batteries should be handled cautiously since eventual internal damage caused can trigger a thermal runaway spontaneously (Tomsic, 2019). A thermal runaway is an accelerating chemical process where increased temperature releases energy, which increases the temperature to release energy and so on further. This is due to the simultaneously changed material characteristics during the additional heat. During a thermal runaway, the cell chemistry may (not LFP) produce oxygen. Therefore it will have all the components available in the so-called fire triangle, oxygen, heat, and fuel (the features which enable fire). This is also why it is difficult to extinguish lithium batteries -They are self-sufficient in these three components during thermal runaway (Tomsic, 2019). One strategy to extinguish a battery fire is to remove the heat by cooling it down, for example, by immersing it in water (Gaines L. L., (Personal communication), 2021b). A damaged battery can be passivated by immersing it in saltwater.

High current may also cause internal damage to the cells resulting in lithium plating (charging), mechanical material stress, heat generation, and concentration gradients (Tomsic, 2019). SEI is sensitive at a low state of charge (SoC).

It is crucial to keep the batteries within limits to ensure performance and a longer lifetime. This is controlled by the BMS (Battery Management System), which is an electronic system that controls the battery system and ensures that the system is used within the margins, according to figure 18 (Tomsic, 2019). Sometimes, however, there may be reasons to adjust the margins depending on the current situation. For example, Tesla did this when they extended the available energy by adjusting the safety margins during hurricane season in Floridan, US 2017 (The Verge, 2017). Personal safety was prioritized over the batteries' eventual degradation. However, use is never permitted beyond permanent damage and safety levels (Tomsic, 2019). Figure 19 visualize the safety margins.

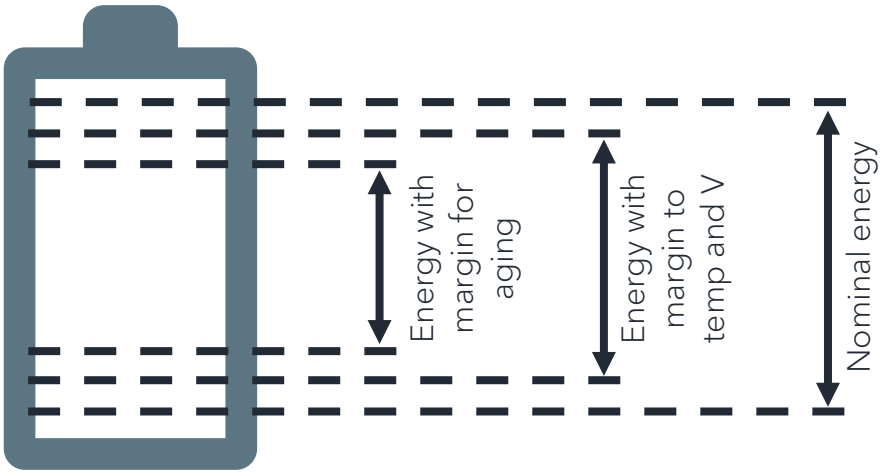


Figure 19. adapted from (Tomsic, 2019).

Most battery cells have a built-in venting mechanism that controls thermal runaway and prevents explosions (Tomsic, 2019). When pressure builds up due to heat and gas evolution, the vent will eventually release. The mechanism may vary between manufacturers and cell types but generally consist of a top disk and a vent hole, see figure 20. When pressure builds up, the disk gets triggered and disconnects the plus pole to prevent current from running through, see figure 21 A (Kong, Xu, Wen, & G. Pech, 2021).The top disk will break at the dedicating scoring, which releases the gases, see figure 21 B.

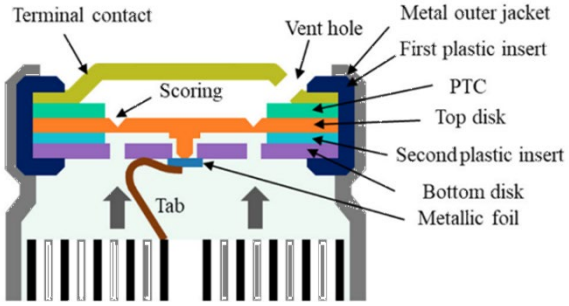
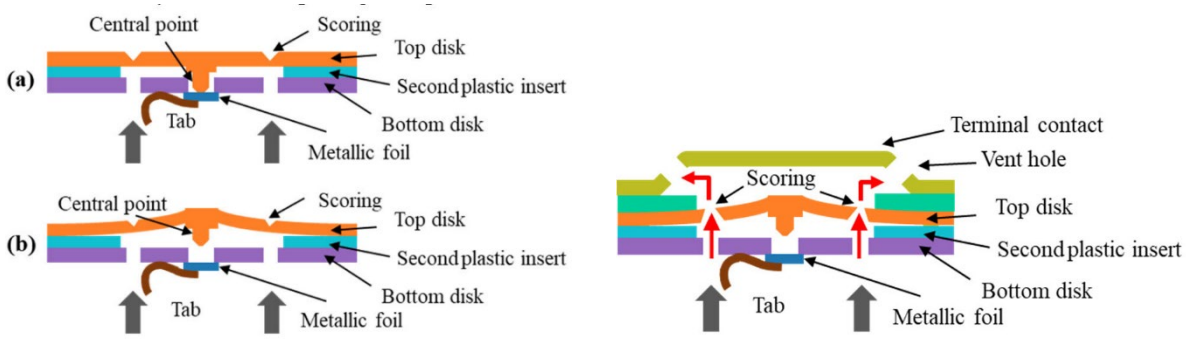


Figure 20. The cap structure of a cylindrical 18650 cell, (Kong, Xu, Wen, & G. Pech, 2021). (Changed by the author; button top removed as not applicable to the study). Disclaimer, copyright through license; https://creativecommons.org/licenses/by/4.0/#



A. Safety functionality. B. Gas release pathway.

Figure 21. The cap functionality. (Kong, Xu, Wen, & G. Pech, 2021). Disclaimer, copyright through license; https://creativecommons.org/licenses/by/4.0/#

4.1.6 Serial- and Parallel Configuration

The nominal voltage of a single lithium-ion battery cell is generally 3,0–4,2 V DC, depending on cell chemistry (Battery University, 2021). The specific energy varies between 150-300Wh/kg. The energy can be calculated as the followed simplified example (Batteriföreningen, 2019):

Energy= capacity*voltage
[Wh = Ah x V]

V=voltage
Ah=amp hour
Wh=Watt hour

The voltage of a single battery cell is usually not enough for larger applications, such as an electric vehicle. Therefore the single cells are connected in various ways to reach desired voltages and capacities. When single battery cells are connected in series, see figure 22, the voltage multiply. The amp-hour will, concurrently, stay the same (Batteriföreningen, 2019). For example, serial-connecting four cells of 3,7 V (DC) and 3,2 Ah give the equation; 4 x 3,7V=14.8 V, while the amp hours remain the same at 3.2 Ah.

Figure 22. Serial configuration.

When single battery cells are connected in parallel, see figure 23, the amp hours multiply (Batteriföreningen, 2019). The voltage, concurrently, stays the same. For example, parallel-connecting four cells of 3,7 V (DC) and 3,2 Ah give the equation; 4 x 3,2Ah = 12,8 Ah, while the voltage remains the same at 3.7 V. Both serial and parallel connections can be made simultaneously and may be configured and combined differently to reach desired system properties.

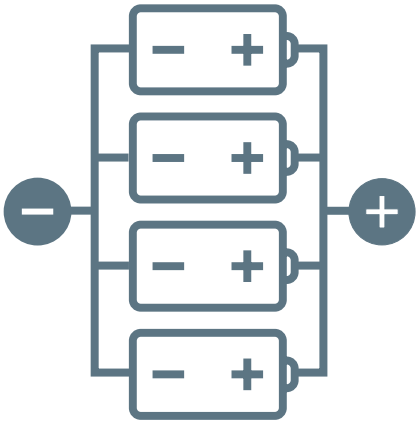


Figure 23. Parallel configuration.

For voltages below 50 V DC, a current passage does not cause any harmful effects to humans in normal cases (Jonsson, Tondel, Carlsson, Bodin, & Blomqvist, 2020). Above 60 V DC is often considered high voltage in electric vehicle applications (BIL Sweden, 2011). The latter is deemed to be hazardous and is subject to special rules, and requires special training. 400 V is standard practice in EVs, while energy storage systems may have even higher voltages (BIL Sweden, 2011). These higher voltages are hazardous to handle and require special training.

4.1.7 Balancing and BMS Functionality

The characteristics vary between individual battery cells, although the cells are of the same type, chemistry, and manufacturer (Tomsic, 2019). This is due to variations in raw materials and production, but minor differences in the environment the battery cells sit in can also affect it. Every single cell is unique in that sense. The differences are slight, but it still affects the performance since the variations make the cells process energy differently. This becomes a problem when cells are series-connected, which they often are (Lundström, 2021). This causes an imbalance between the cells over time (see figure 24, which symbolizes four serial-connected battery cells in imbalance).

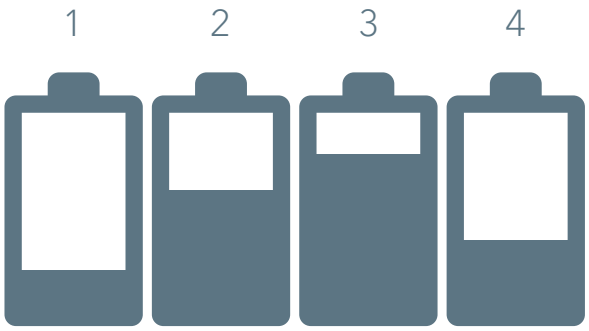


Figure 24. An imbalance between battery cells.

When current is drawn from the battery system (as when using it), an equal amount of charge is extracted from each individual cell simultaneously (Lundström, 2021). Figure 25 shows that the cell with the lowest level (1) will reach the bottom level first when the current is drawn from the system. Although there is energy left in the other cells, this cannot be extracted, as in the example to the right in figure 25.

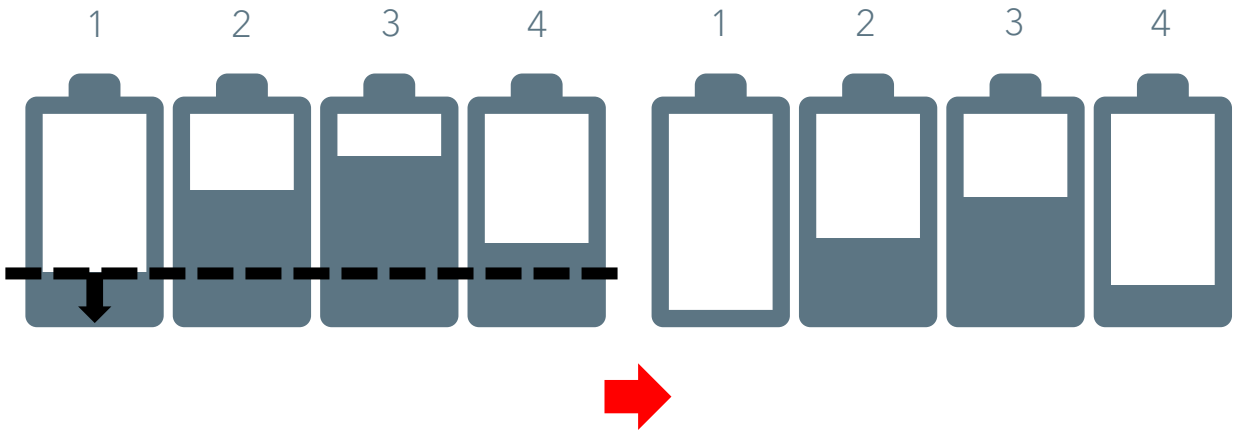


Figure 25. Battery levels before discharge to the left and after discharge to the right.

The same applies to charging the system (Lundström, 2021). The cell with the highest level (3) will reach the upper limit first, and when this happens, it is not possible to charge the other cells further. The varying levels decrease the capacity for the whole battery system since the highest and lowest levels set the limits. Therefore, it is crucial to keep the batteries at an even level to access the total capacity of the battery system, see figure 26. Again, this applies when cells are serial connected. When cells are parallel connected, each parallel row will even out automatically, but any series steps are affected by the phenomenon.

Figure 26. Batteries have the same levels.

The battery cells' energy level is also referred to as SoC (State of Charge) (Lundström, 2021). The BMS (Battery Management System) collects information about the SoC (State of Charge) and adjusts energy levels to keep the cells balanced. The BMS also keeps track of temperatures and the so-called SoH (State of Health).

Battery cells generate heat during charge and discharge (usage) (Lundström, 2021). In addition, the heat increases faster in the outer limits of the SoC span. This is because the internal resistance is higher at about <20% SoC and >80% SoC, depending on cell chemistry, type, and brand. This mainly affects how fast or slow a battery can be charged and discharged in these SoC areas. During the critical areas, the power is lowered to maintain an allowed temperature. The BMS thoroughly monitors and controls this.

Lithium-ion batteries operate typically best at about 22-35°C, though it might vary depending on cell chemistry, type, and brand (Lundström, 2021) (Battery University, 2021). Similarly, the allowed discharge temperatures usually stay between -20 to 60°C (Battery University, 2021). The allowed charge temperature is typically between 0 to 45 °C.

4.2 Legislation

The EU uses laws and regulations to control lithium-ion batteries (LIBs) in automotive applications throughout its life, and several are represented in figure 27.

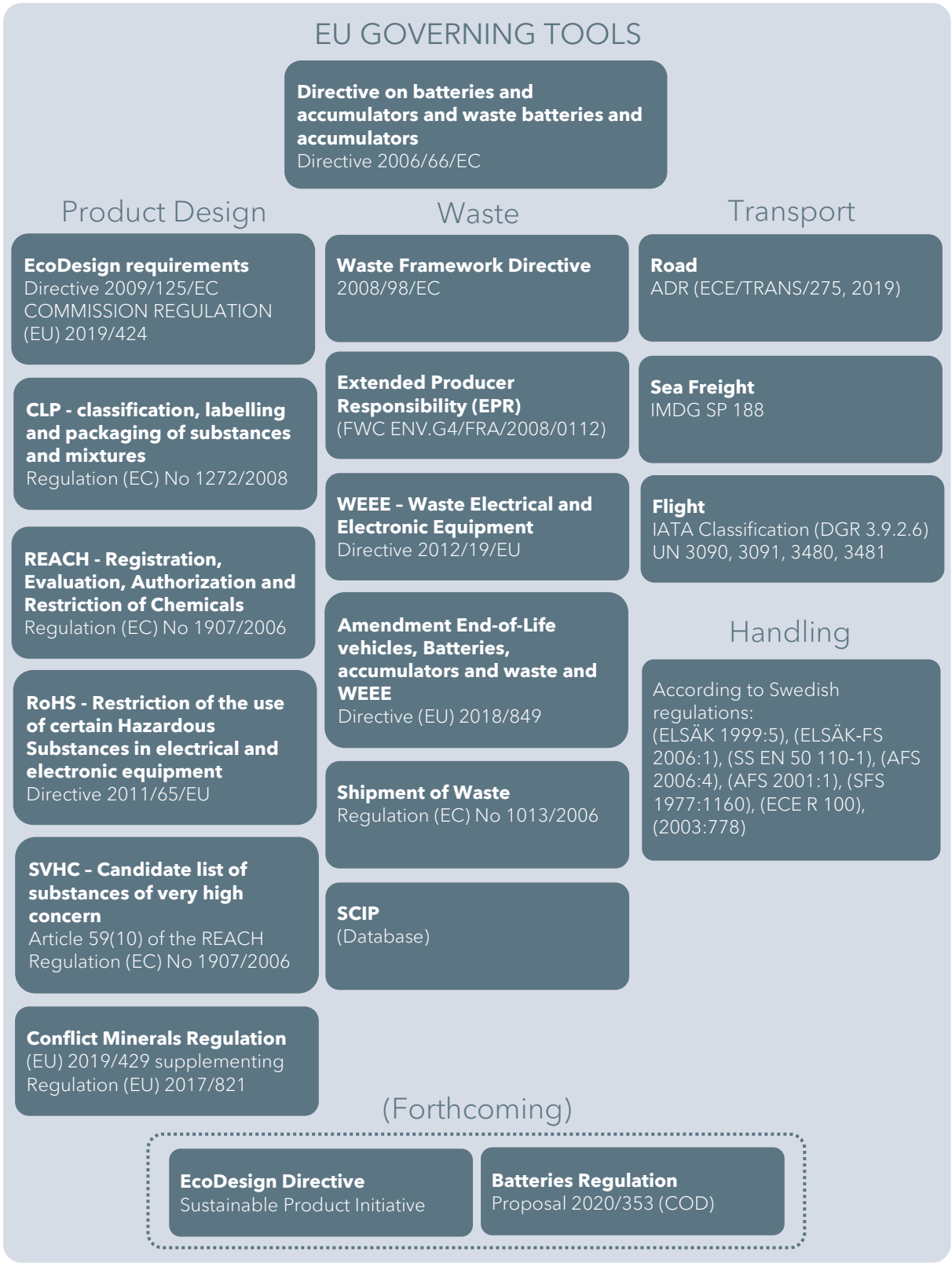


Figure 27. EU Governing tools outlook for handling automotive LIBs, adopted by (Samarukha, 2020) (BIL Sweden, 2011).

The Battery Directive 2006/66/EC in figure 27 covers li-ion batteries (EUR-Lex, 2006a). This Directive has been deficient and not directly intended for lithium-ion batteries but rater batteries in general (Mathieu, 2021). Therefore, the EU Commission has initiated reframing the old Directive for a forthcoming update covered in subchapter *4.2.1 Battery Directive* (EUR-Lex, 2020).

The EU Commission has also started a feasibility study called Sustainable Product Initiative to widen the EcoDesign Requirements Directive 2009/125/EC in figure 27 (European Commission, 2021c). Taken together, this is covered in subchapter *4.2.2 EcoDesign Directive*

Other laws and regulations in figure 27 cover specific areas, briefly explained in the subchapters *4.2.3 Product Design, 4.2.4 Waste, 4.2.5 Transport, and 4.2.6 Handling*. Finally, an overview of laws in some other countries is given in subchapter *4.2.7 Legislation Around the World*.

4.2.1 Battery Directive

As a part of The European Green Deal, the EU Commission initiated a pre-study to reframe the Battery Directive 2006/66/EC (European Commission, 2021d). Except for including the requirements from the old Directive, the new Directive also aims to incorporate sustainability requirements covering technical, economic, environmental, market, and societal aspects (EUR-Lex, 2020). The revised Directive proposal is under consultation at the time of writing and expects to enter into force 1st of January 2022 with a gradual implementation as of 2023 (Mathieu, 2021). Although not in force, the Directive is still expected to provide stricter rules (Armand, et al., 2020). Some of the potentially most significant changes are briefly described as follows, but this thesis does not go into further detail since the Directive not yet have been set.

The new Directive proposal is divided into so-called measures, which address the whole value chain in a more holistic approach, mapped out in figure 28 (European Commission, 2020). The consultancy Circular Energy Storage have analyzed the proposal and claims that:

> - *"The new regulation introduces requirements on labeling, maximum carbon footprint, recycled content, value chain due diligence, third party access to battery information and higher recycling efficiency and collection targets."* (Melin, 2020)

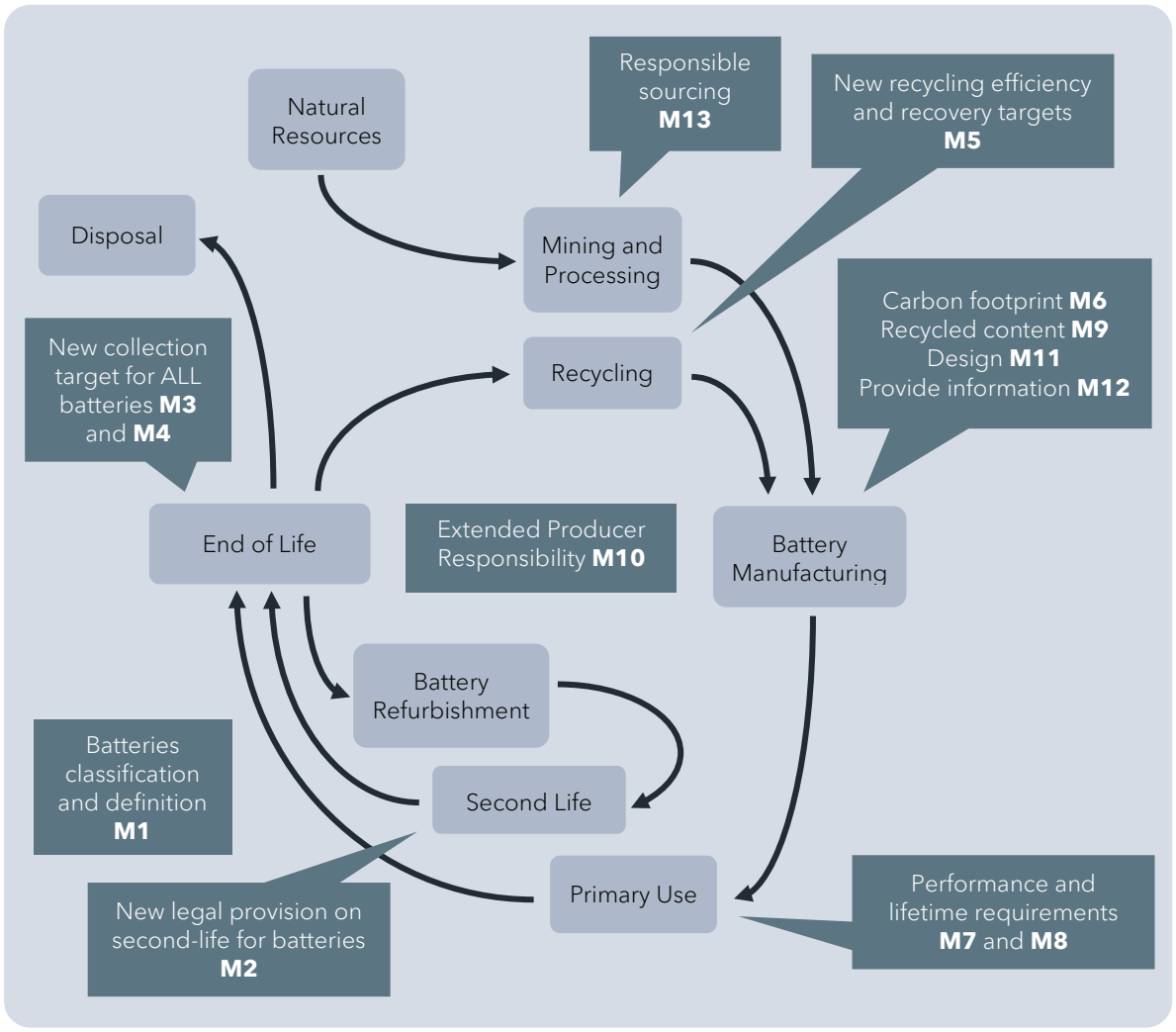


Figure 28. Measures in the new battery directive related to the value chain, adapted from (Petranikova, 2021) (European Commission, 2020).

The previous directive 2006/66/EC stated a recycling rate of 50% for lithium-ion batteries, and it was based on the average battery weight (EUR-Lex, 2006a). This has been problematic as there is room for interpretation of what is included in the total weight, for example, by including other components than battery cells themselves. The new proposal suggests an increased recycling rate in general and increased recycling rates for specific materials such as Co, Ni, Li, and Cu (European Commission, 2020). There are also requirements for recycled material content in new batteries of active materials from old batteries. The implementation will gradually begin with the companies only having to report the recycling content in new batteries by 2027 to demand actual levels of recycled content in 2030 (EUR-Lex, 2020). Altogether these figures are summarized in figure 29. . The new directive can be challenging for numerous battery recycling actors on the market with low recovery levels and selectivity (Armand, et al., 2020).

M5 – Recycling Rate:

	2025	2030
Rate	65%	70%

M5 - Materials Recovery:

	2025	2030
Co	90%	95%
Ni	90%	95%
Li	35%	70%
Cu	90%	95%

M9 - Recovered materials in New Batteries:

	2027	2030	2035
Co	inform	12%	20%
Ni	inform	4%	12%
Li	inform	4%	10%

Figure 29. EU Battery Directive – Recycling and recovery rates (EUR-Lex, 2020).

4.2.2 EcoDesign Directive

Production, consumption, and waste stand for about 40% of the world's greenhouse gas emissions (European Commission, 2021c). Consumption increases globally, and without action, it is expected to exceed a consumption rate that is three times faster than the earth has time to reproduce by 2050. Simultaneously the waste generation increases.

To meet these challenges, the European Commission embarks extensive climate work. This includes an overview of the ecodesign directive (European Commission, 2021c). The new Directive aims to make products sold on the European market more sustainable through further legislative measures. More sustainable products that are energy efficient and may be repaired are beneficial for consumers, nature, and the climate. The new directive is expected to enter into force during the fourth quarter of 2021.

The previous EcoDesign Requirements Directive 2009/125/EC focused on products' energy efficiency (Mathieu, 2021) (EUR-Lex, 2009). The new Directive evolves by including the whole life cycle and addresses circular design. In addition, the Directive will also restrict toxic chemicals in products such as (European Commission, 2021c).

- Electronics & ICT Equipment
- Textiles
- Furniture
- Steel, Cement & Chemicals.

4.2.3 Product Design

Numerous regulations regarding product design cover chemical compounds. The rules generally ensure that the material chosen does not contain hazardous chemicals for humans and nature, which is regulated by ECHA (European Chemicals Agency) (ECHA, 2021a).

A substance is not automatically entirely safe just because it is regulated (RISE, 2021). Some substances are strictly forbidden, while others are allowed in regulated amounts or under certain conditions. It also takes time to legalize substances simultaneously as new substances constantly evolve. Some companies act internally by banning one or all groups of substances (RISE, 2021). Such substances can be found in the company's RSL (Regulated Substances List), which is an entirely voluntary approach.

REACH
REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) means that those who produce, import, or sell goods and chemicals in the EU/EES need to follow regulations of the specific business (Swedish Chemicals Agency, 2021a) (ECHA, 2021b). The law includes rules of the registration of substances, bans or other substances restrictions, requirements of permits for particularly hazardous substances, and regulations for informing customers. The statute also contains rules for users regarding the use of chemical products.

RoHS
RoHS (Restriction of Hazardous Substances) aims to substitute and limit hazardous chemicals in electrical and electronic equipment to minimize the risks for human health and the environment (EUR-Lex, 2011) (Swedish Chemicals Agency, 2021b). The directive also intends to enhance the possibilities of profitable and sustainable material recycling from electrical and electronic equipment.

SVHC
The so-called candidate list (of Substances of Very High Concern) lists especially hazardous substances and is part of the EU chemicals legislation REACH (Swedish Chemicals Agency, 2021c). Those who produce, import, or distribute goods or chemical products within the EU and EES must keep track of whether the goods contain any substances on the candidate list since this may require special obligations.

CLP
CLP is a regulation containing rules (for Classification, Labelling, and Packaging of substances and mixtures) (EUR-Lex, 2008) (Swedish Chemicals Agency, 2021d). It also includes laws of reporting data for substances and mixtures. The CLP regulation must be met in order to place a chemical product on the European market.

Conflict Mineral Regulation
Mineral trade within politically unstable areas is problematic since it may be used to fund armed groups, corruption, and money laundering (European Commission, 2021e). It may also lead to abuse of human rights and forced labor as well as grow armed conflicts. The EU Commission initiated a regulation to stem mineral trade from these conflicts and high-risk areas. According to the EU Commission (European Commission, 2021e), these areas are those:

- *"Whose natural resources include minerals which are in high demand, either locally, regionally or globally."*
- *"Are either suffering from armed conflicts, such as civil war, a state of fragile post-conflict, or witnessing weak or non-existing governance and systematic violations of international law, including human rights abuses."*

The regulation covers the four minerals - tin, tungsten, tantalum, and gold (also known as the 3TG minerals) (European Commission, 2021e). These minerals are all mined in the Democratic Republic of Congo (DRC), which is a critical area in this context (Järeskog, 2021). DRC does not stand for all 3TG mineral volumes mined, but it is commonly addressed due to severe issues. Most of today's tantalum also originates from Africa's Great Lake Region, including Rwanda, DRC, and Burundi (Barume, Naeher, Ruppen, & Schütte, 2016). Small volumes of tin, tungsten, and gold are also mined here. The 3TG minerals can be found in everyday products, from mobile phones to cars and laptops (European Commission, 2021e). The regulation says that companies who use 3TG minerals or manufacture products containing them are obliged to find out whether they relate to conflict minerals or not (EUR-Lex, 2019). The regulation has only been active from January 2021 but has already met critique at the time of writing. According to Mikael Järeskog, policy chief at PMU, several member states interpret the regulation and hide the list of national companies covered by it (Nyamai, 2020). There is no direct consequence of violating this law today, according to Järeskog (Järeskog, 2021). If a company has imported too much of a conflict mineral, they will only receive a notice. Cobalt is not included in the Conflict Mineral Regulation, but Järeskog argues it should be (Järeskog, 2021). In addition, 50-60% of the world's cobalt originates from DRC (Järeskog, 2021).

4.2.4 Waste

The addressed laws regarding waste aim to protect people and the environment (Swedish Environmental Protection Agency, 2021a). It also affects development towards a more sustainable and circular course.

Waste Framework Directive
The Waste Framework Directive 2008/98/EC is about waste management and brings up the so-called waste hierarchy of; prevent, reuse, recycle, recover, and disposal (European Commission, 2021b). Earlier described in chapter 2. THEORY.

EPR
EPR (Extended Producer Responsibility) is an environmental policy used in many countries over the globe (Swedish Environmental Protection Agency, 2020a). It implies that the producer's responsibility follows the product to its end of life to encourage sustainable product development. EPA includes obligations such as ensuring that all batteries sold are collected and recycled. To achieve this, producers often enter into agreements with another party responsible for collecting and recycling for a fee, for example, El-kretsen in Sweden (El-Kretsen, 2017). All electronics with built-in batteries are covered with two regulations in Sweden called *SFS 2014:1075* and *SFS 2008:834* (Swedish Environmental Protection Agency, 2021b).

WEEE
The WEEE - Waste Electrical and Electronic Equipment Directive 2012/19/EU means all producers and distributors are responsible for taking care of electrical and electronic equipment waste (EUR-Lex, 2012). The responsibility also includes ensuring that the waste is handled correctly to be recycled (Swedish Environmental Protection Agency, 2020b).

Amendment End-of-Life vehicles, Batteries, accumulators and waste and WEEE
Directive (EU) 2018/849 was part of EU's so-called Waste Package that entered into force on the 1st of July 2018 (EUR-Lex, 2018). The package's overall goal was to reduce waste volumes, increase reuse of products, increase recycling, and improve waste management.

Shipment of Waste
Regulation (EC) No 1013/2006 regulates cross-border shipments of waste (EUR-Lex, 2006b). It is based on the Basel Convention and the OECD agreement (Organization for Economic Co-operation and Development) on waste shipment. (European Commission, 2021b)

SCIP
As of January 1st of 2021, companies who produce, import, or supply products containing substances of concern must report this to the SCIP database in order to place a product on the European market (Swedish Chemicals Agency, 2021e). It relates to the Waste Framework Directive, which aims to reduce hazardous chemicals in waste and promote substitution to safer alternatives. It also aims to ensure that dangerous substances are not used in recycled materials. The Swedish Chemical Agency provides a tool for the substitution of materials called PRIO.

4.2.5 Transport
According to the UN test and criteria manual, lithium-ion batteries must undergo certain test requirements to be transported, often called UN38.3 testing (Batteriföreningen, 2019). Other transport regulations also include IATA, ADR, and IMDG, stated as follows:

IATAs - Dangerous Goods Regulation on flight transport

ADR - Road transportation regulation. MSB – Swedish Civil Contingencies Agency publishes the Swedish version.

IMDG - Regulation covering ship freight.

4.2.6 Handling
Battery handling requires some caution and is governed by specific rules. According to the trade association BIL Sweden, the following list of laws, standards, and manuals describe the safe handling of vehicles with fully or partially electric drive systems.

List adapted from (BIL Sweden, 2011):

- National Electrical Safety Board's regulations and general advice (ELSÄK 1999:5) for definitions and explanations of terms.
- National Electrical Safety Board's regulations (ELSÄK-FS 2006:1) and general advice on electric safety when working in a professional operation.
- Applicable parts of Swedish Standard (SS EN 50 110-1) for care of electric facilities.
- Swedish Work Environment Authority's regulations (AFS 2006:4) on use of work equipment.
- Swedish Work Environment Authority's regulations (AFS 2001:1) on systematic work with work environment issues and general advice on applying the regulations
- Work Environment Act (SFS 1977:1160) 3 chap. 2 § informs of the employer's main responsibility for the work environment
- Rules for approving (ECE R 100) electric cars with regards to design and safety
- The law regarding protection against accidents (2003:778) 2 chap. 2 § describes applicable requirements for fire protection.

In addition to the list, the trade association BIL Sweden has also produced guidelines for handling electric cars in Sweden that have had an accident available at their website

(Elbilsinfo, 2021). The guidelines describe different approaches per actor, e.g., for emergency services, insurance companies, rescuers, private individuals, car assemblers/recyclers, car repair shops.

4.2.7 Legislation Around the World

Laws and regulations for li-ion batteries vary across the world. This chapter gives a quick view and focuses on battery recycling.

United States
The regulation differs across the United States. The battery recycling program called call2recycle (call2recycle, 2021) divide the legislative overview of the United States into three categories (at the time of writing) counted on; the 50 states, the federal District of Columbia, and the territory Puerto Rico:

- State battery recycling requirements in effect
  (Adapted by 22 areas, such as California and Texas)
- Producers required to offer or fund battery recycling
  (Adapted by 8 areas, including New York, Florida, and Puerto Rico)
- No battery recycling requirements
  (In 22 areas, including Ohio and the District of Columbia)

Some member states have adopted the EPR – Extended Producer Responsibility for rechargeable batteries (Battery Recycling, 2014).

Japan
The Law for the Promotion of the Effective Utilization of Resources entered into force in 2001 and aimed to integrate the 3Rs (Reduce, Reuse, Recycle) to create a sustainable society according to METI – *Ministry of Economy, Trade and Industry*, which is a ministry of the government of Japan (METI, 2007). The law state that all manufacturers and importers of rechargeable batteries, and equipment containing rechargeable batteries, must implement a recovery system (Csiro, 2018). According to the Battery Association of Japan, the recovery target for Li-ion batteries is 30% (Battery Recycling, 2014) (BAJ, 2021).

China
A new regulation entered into force in China on the 1st of January 2020, covering the recycling of used energy vehicle (NEV) power batteries (Argus, 2020). The law states recovery rates for nickel, cobalt, manganese, and lithium.

4.3 Recycling Electronics Waste

Electrical products are the fastest growing waste fraction worldwide (El-Kretsen, 2017). The electrical waste consists of substances that are directly toxic to the environment, such as lead (Pb), cadmium (Cd), and mercury (Hg).

Stena Recycling AB is the leading recycling company in Sweden and recycles electronic waste at their recycling facility Stena Nordic Recycling Center (SNRC) in Halmstad, Sweden (Stena Recycling AB, 2021a). An overview of the recycling flow is described in figure 30 (Stena Metall, 2015)(Study visit at SNRC - Stena Nordic Recycling Center, 2021 March 16). The first step of Stena's electronics waste recycling process is to sort the appliances, remove hazardous waste and collect reusable components such as processors, RAM, SSD, hard disk drives, graphic cards, and power supply units (Stena Recycling AB, 2021b). Batteries are considered hazardous waste as well as oil, lead, asbestos, capacitors containing dangerous chemicals, and toner (Stena Metall, 2015). Removing the hazardous chemicals ensures that they do not end up in the environment or contaminate other waste streams and fractions.

When the electronics have been dismantled, they enter the so-called PMR process (Precious metal recycling) and PRC process (Plastics recycling) (Stena Metall, 2015), see figure 30. The electronics are loaded to a shredder where it is torn down to material fractions. The fractions enter a magnet drum that separates ferrous metals and copper from the other parts. The copper is further manually separated from the ferrous. The remaining parts of non-ferrous metals and plastics are divided according to their size through strains. After size separation, fractions of similar size go through a so-called eddy current separator where non-ferrous metals such as aluminum and circuit boards are separated (Stena Metall, 2015). Sensors are also used, and it is easier for the sensors to recognize different materials if they have the same size (Leppäjoki, 2021)(Study visit at SNRC, 2021). Circuit boards are further detected and sorted by their characteristic green color in an optical separator, separating it from the aluminum. The main waste stream is processed on shaking tables dividing the materials into precious metals (with high copper content) and other (Stena Metall, 2015).

The plastic mix enters a controlled flotation process to separate the different plastics according to density (Stena Recycling AB, 2021c), see figure 30. It separates the plastics into recyclable plastics and bromated plastics. Bromated plastics contain flame retardants and are considered toxic, though their toxicity might vary (Swedish Environmental Protection Agency, 2020c). All types of bromated plastics are difficult to degrade. The bromated plastic is usually sent to incineration. It is essential to separate the bromated plastics since they may contaminate the other fraction.

The recyclable plastics are shredded and go through a second wet density separation process (Stena Recycling AB, 2021c), see figure 30. Then it is dried to continue to a separation of the plastic types through electrostatic separation. It may, for example, be separated into PS and ABS. The plastics are further divided by color. Pellets are created from recycled plastics through an extrusion process to create ABS-pellets and PS-pellets, which get further distributed to manufacturers (Stena Metall, 2015).

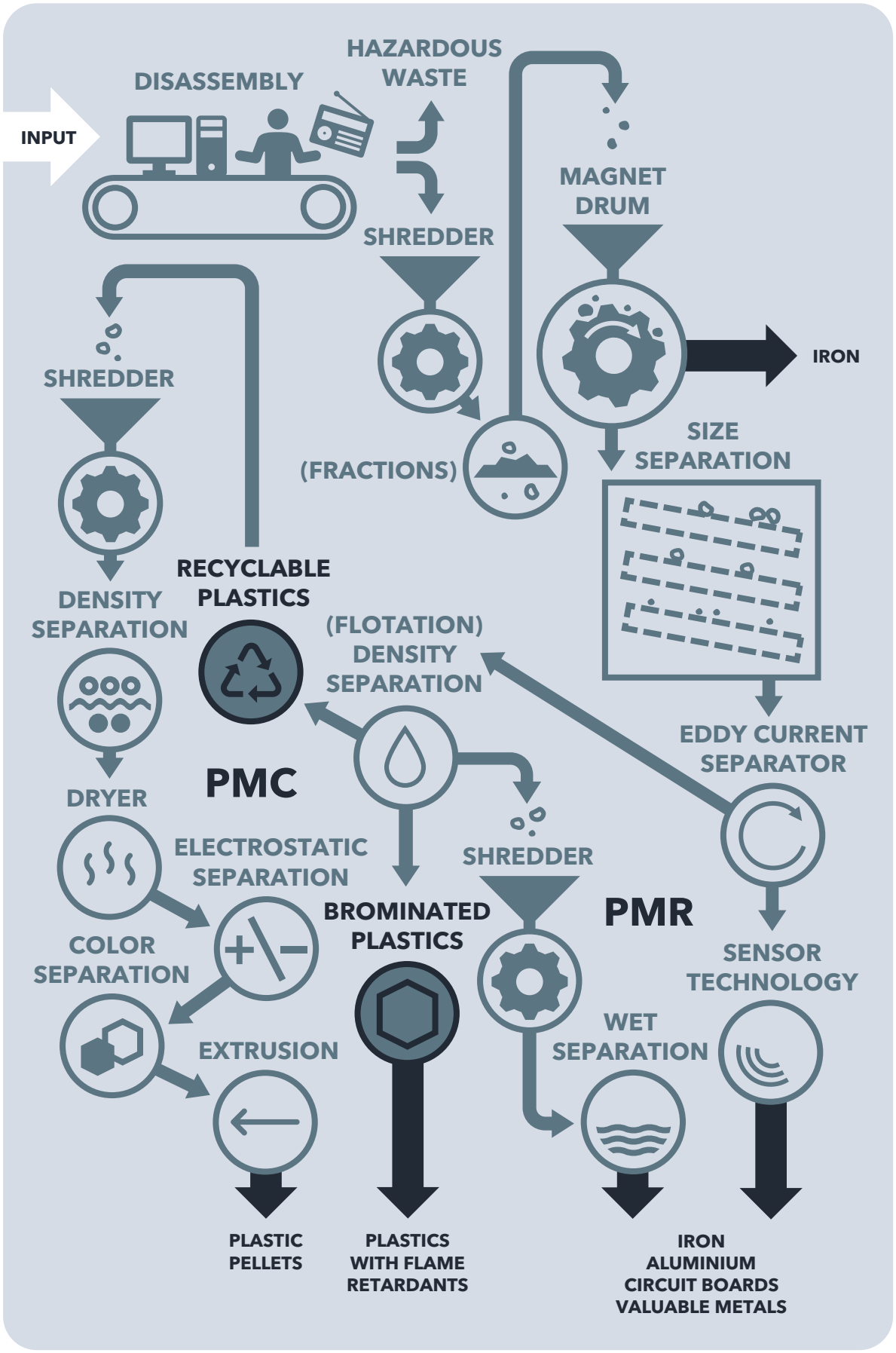


Figure 30. Electronic Waste Recycling (Stena Metall, 2015)(Study visit at SNRC, 2021).

4.4 Recycling Li-ion Batteries

EV sales grew by 43% in 2020 worldwide (EV-volumes, 2021). Lithium-ion batteries in EVs are expected to increase by ten times in the coming decade, and the demand for recycling will likely increase simultaneously (Stena Recycling AB, 2021d) (Armand, et al., 2020). Recycling will be necessary to save critical metals from the battery waste streams, such as lithium, nickel, and cobalt (Gaines, Richa, & Spangenberger, 2018). Both to secure future material supplies and to reduce the carbon footprint of lithium-ion batteries and EVs. Figure 31 shows an example outlook of battery recycling through hydrometallurgy.

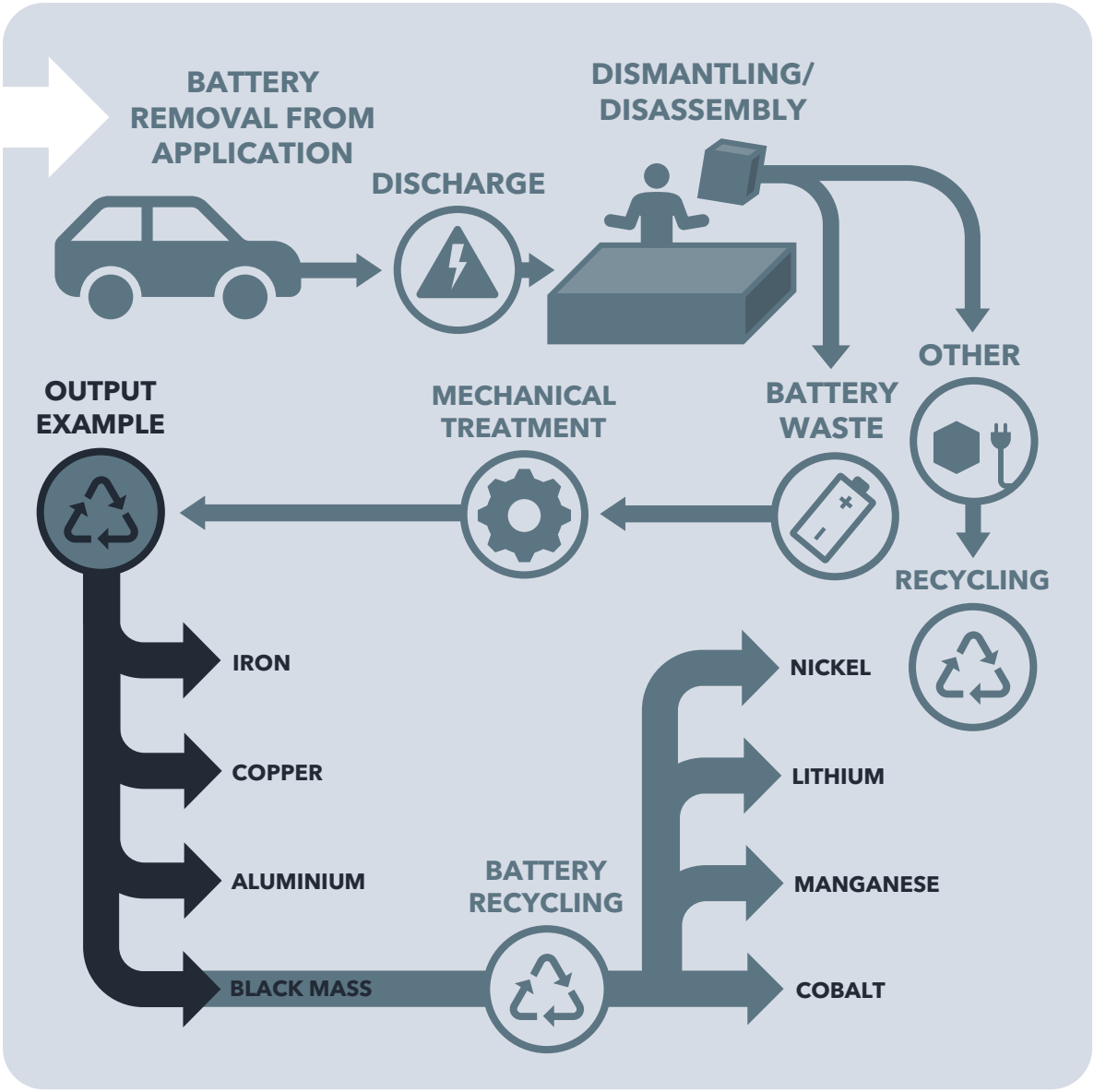


Figure 31. Hydrometallurgy, adopted from (Ekberg & Petranikova, 2015).

It is possible to adopt different strategies to recycle lithium-ion batteries, and the general approaches can be divided into pyrometallurgy, hydrometallurgy (with or without thermal pretreatment), and direct recycling (Gaines L. , 2018). Some strategies require the batteries to be pre-processed by discharge, dismantling, and mechanical pre-treatment (with one exception for pyrometallurgy, where those steps are optional), altogether described in the following subchapters. Some recycling strategies use similar technologies, although the

pathway may differ. (Ekberg & Petranikova, 2015). Recovered materials (depending on cell chemistry and exact recycling process) can generally be (Harper, et al., 2019):

- Aluminum
- Nickel
- Lithium
- Manganese
- Cobalt
- Graphite
- Plastics

Recycling will not be enough to supply the increased demand for lithium-ion battery materials until the necessity slows down (Gaines L. , 2018). However, the advantages of recycling are still instant as it can cut down disposal costs, reduce environmental impacts, and reduce reliance on imported materials.

4.4.1 Discharge

After removing the batteries from their application and before dismantling and mechanical pre-treatment, they generally get fully discharged (Ekberg & Petranikova, 2015). The discharge ensures safety in the further steps by preventing electric shocks, short circuits, and sparks (Leppäjoki, 2021).

4.4.2 Dismantling/Disassembly

Manual disassembly is a common practice for larger EV batteries (Ekberg & Petranikova, 2015). Automated disassembly is being investigated on a research-level but has obstacles to overcome before it becomes a reality on a larger scale. The primary strategy is to separate the batteries (single cells or more commonly as modules) from busbars, cables, circuit boards/steering units, cooling systems, and casings (Ekberg & Petranikova, 2015). The batteries are sent to the battery recycling plant, while the other components are sent to general recycling facilities. The required level of disassembly partially depends on the physical size of the battery system. Generally, smaller portable batteries are not disassembled at all, while larger systems require some level of disassembly.

4.4.3 Mechanical Pre-treatment

The mechanical treatment breaks down the parts by crushing, grinding, and shredding. The goal is to disconnect different types of material into pure material fractions, which are then separated to be sent to each intended recycling stream. The black mass contains valuable materials such as cobalt and lithium. It is essential to separate the black mass from other materials such as aluminum, copper, plastics, steel, circuit boards, etc. (Ekberg & Petranikova, 2015). The latter materials are separated into their main fraction to be further recovered at regular recycling facilities. The mechanical treatment can be conducted through a sequence of steps to ensure refinement and reach a high purity of the black mass. Some companies only perform the mechanical treatment of the lithium-ion battery recycling process (Armand, et al., 2020). They separate the materials to sell them to different actors. Metals are generally sold to metal producers, and the black mass can be sold to specialized battery recycling plants or to battery manufacturers who have a recycling setup.

4.4.4 Pyrometallurgy

The pyrometallurgical recycling process heats the materials to high temperatures during incineration (Ekberg & Petranikova, 2015). The batteries can be discharged to a certain level for personal safety when handled. However, the batteries do not need to be discharged before the pyrometallurgical process specifically. They can be sent directly to the incinerator as they are. Charged batteries are advantageous since their energy contributes to heat generation in the combustion process. Thus, less added power is required. A battery system can be disassembled before pyrometallurgy to separate materials and recycle them in the respective recycling stream, such as cables and bus rails. It increases material recycling for these specific parts, but it is not required. Thus, batteries can be mounted in a module or an entire system when sent for pyrometallurgy. It depends on the size limit of the specific incineration plant. As a result, some materials will burn during the process, such as plastics and all other organic compounds (Ekberg & Petranikova, 2015). An example of li-ion battery recycling through pyrometallurgy is shown in figure 32. The output from pyrometallurgy is metal alloys consisting of cobalt, copper, iron, and nickel (Armand, et al., 2020). These alloys are processed by hydrometallurgy to access the materials separately. The aluminum, manganese, and lithium are lost in a glass structured slag product. These materials can be recovered through hydrometallurgy but are generally not due to complexity and lack of economic motives. Instead, the glass structured slag product is crushed and used in road construction.

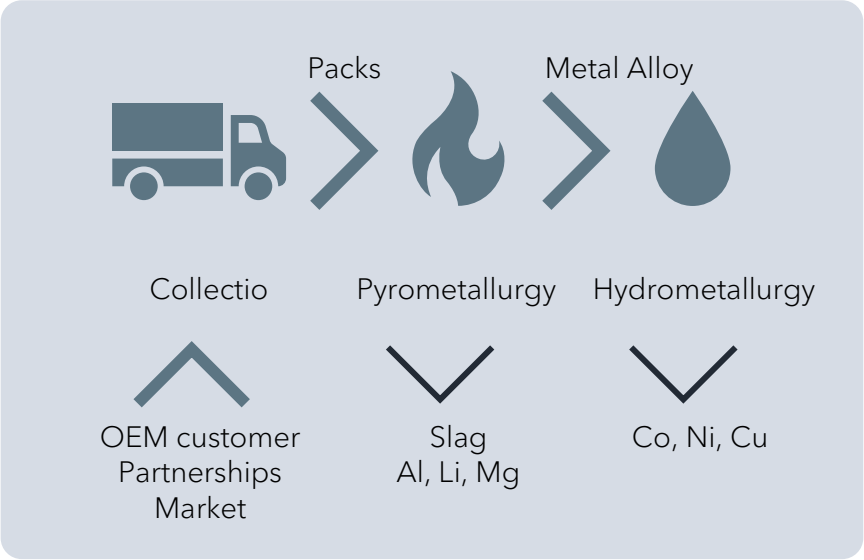


Figure 32. Possible recycling flowchart of pyrometallurgy (Ekberg & Petranikova, 2015) .

Pyrometallurgy can be considered a robust process. Practically, it can handle any cell chemistry, type, size (depending on the specific plant), and configuration. However, as part of the sustainability work, especially in Europe, pyrometallurgy (and other combustion methods) are expected to pay higher taxes for greenhouse gas emissions

4.4.5 Hydrometallurgy

Before hydrometallurgy, the batteries are pre-processed through discharge, dismantling, and mechanical pretreatment with size adjustment and material separation (Ekberg & Petranikova, 2015). The most important is to separate the black mass from other materials such as metals, printed circuit boards, plastics, and cables which are further processed in separate recycling streams (Armand, et al., 2020). The black mass is processed through hydrometallurgy, either alone or combined with a preceding thermal pre-treatment that heats the materials below the melting point of the primary metals (Armand, et al., 2020). Hydrometallurgy itself involves leaching, solvent extraction, and precipitation. The output of hydrometallurgy is cobalt, lithium, nickel, and manganese. The combination of hydrometallurgy and thermal pre-treatment give higher recovery rates than hydrometallurgy alone, and it is therefore considered the more modern approach (Armand, et al., 2020). The thermal pretreatment removes the organic compounds such as organic binders and graphite since they may cause problems during the process (Armand, et al., 2020). The thermal treatment can be conducted with the presence of oxygen (referred to as incineration) or the absence of oxygen (called pyrolysis), where pyrolysis is considered the more environmental-friendly alternative. An example of a li-ion battery recycling flowchart is shown in figure 33, describing the battery manufacturer Northvolts process (Northvolt, 2021).

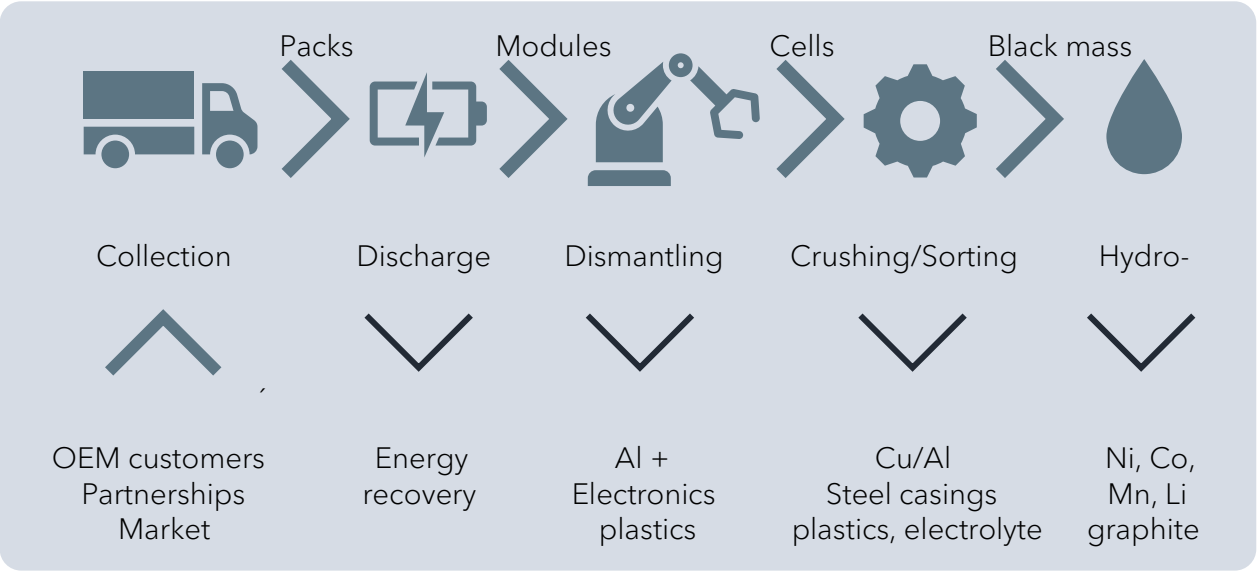


Figure 33. The hydrometallurgy recycling flowchart (Northvolt, Cell to cell: creating a circular European battery industry, 2021).

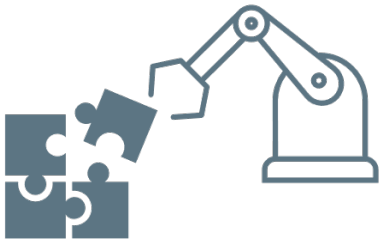
Hydrometallurgy can accomplish high levels of material recovery with as much 80-99% for lithium and cobalt (Armand, et al., 2020). The purity output makes it possible to use the materials in manufacturing to produce new lithium-ion batteries. A study shows that recovered material from spent LIBs through hydrometallurgy could be processed to accomplish a comparable quality of primary material used in battery production (Ekberg & Petranikova, 2015). However, the recovery rate is highly affected by the purity of the input black mass. Eventual remains of other materials in the black mass can affect the process. Some materials have no interference, while others can significantly impact and hinder material recovery. Therefore, the demands on mechanical separation are high. Impacting materials are often referred to as impurities or contamination of the black mass and are generally aluminum, copper, and iron (Petranikova, 2021). Aluminum is difficult to separate and can affect the leaching and hinder the recovery of lithium in hydrometallurgy (Ekberg & Petranikova, 2015). The cell chemistry called NCA has aluminum foil in its cell compound. These foils also need to be separated before being processed through hydrometallurgy. It is done through a mechanical separation after the cell has been shredded down. Tin is also unsatisfactory for hydrometallurgy, not in small amounts, but it should be avoided (Petranikova, 2021). Tin is common in electronics and PCBs, motivating to separate these components before processing. If eventual copper fragments stay in the black mass, they may still be recovered through hydrometallurgy, but it is better to separate them earlier. Polymers(such as plastics) do not interfere with hydrometallurgy, but on the contrary, they can be contaminated by battery chemicals (Petranikova, 2021). Graphite does not interfere significantly with the leaching process. Graphite is dusty and may contaminate other fractions, requiring it to be removed, e.g., by washing it away (Leppäjoki, 2021).

Hydrometallurgy is considered the most promising method to accomplish circularity in the li-ion battery value chain (Armand, et al., 2020). It is also an excellent approach to meet the requirements of the new EU battery directive thanks to the high recovery rates and since it, unlike other methods, can recover lithium. The electrolyte evaporates quickly and is often not recycled, but at least one company claims to have managed to recover the electrolyte at the time of writing (Petranikova, 2021).

The hydrometallurgical process is mainly used in battery recycling on the Asian continent in countries like China and South Korea, which is quite natural since this is where most of the

world's lithium-ion batteries are produced (Armand, et al., 2020). But more companies start to pop up on other continents at the time of writing, such as Northvolt in Sweden. A company called Lithion in Canada also uses hydrometallurgy and claims to have a fully automated process and a black mass recovery rate of over 98% (Lambert, 2021). By processing the black mass through hydrometallurgy, Lithion produces metal salts and a final product containing cobalt, nickel, manganese sulfates, lithium carbonate, and graphite. The company also claims that the batteries do not need to be discharged before processing through their specialized technology.

4.4.6 Direct Recycling



Direct recycling is also called cathode-to-cathode recycling and mainly consists of mechanical separation (Gaines L. , 2018). The approach requires pre-processing of the batteries by discharge and dismantling, see figure 34. The strategy is further to separate the black mass from the other components. Then the black mass is divided by its different compounds to recover the materials without causing any chemical changes (Gaines L. L., 2021a). Unlike other technologies like hydro- and pyrometallurgy, direct recycling does not break down the molecular components of the black mass. Instead, the strategy is to maintain the existing structure of the cathode material as much as possible. It is a complex crystal structure, and it constitutes the actual performance and the value of the cathode material. The process makes it possible to recover the cathode by a low level of treatment and with low costs. Direct recycling technology is mainly performed on a lab scale but can be a promising future commercial technology, according to Linda L. Gaines, a Systems Analyst at Argonne National Laboratory (Gaines L. L., 2021a).

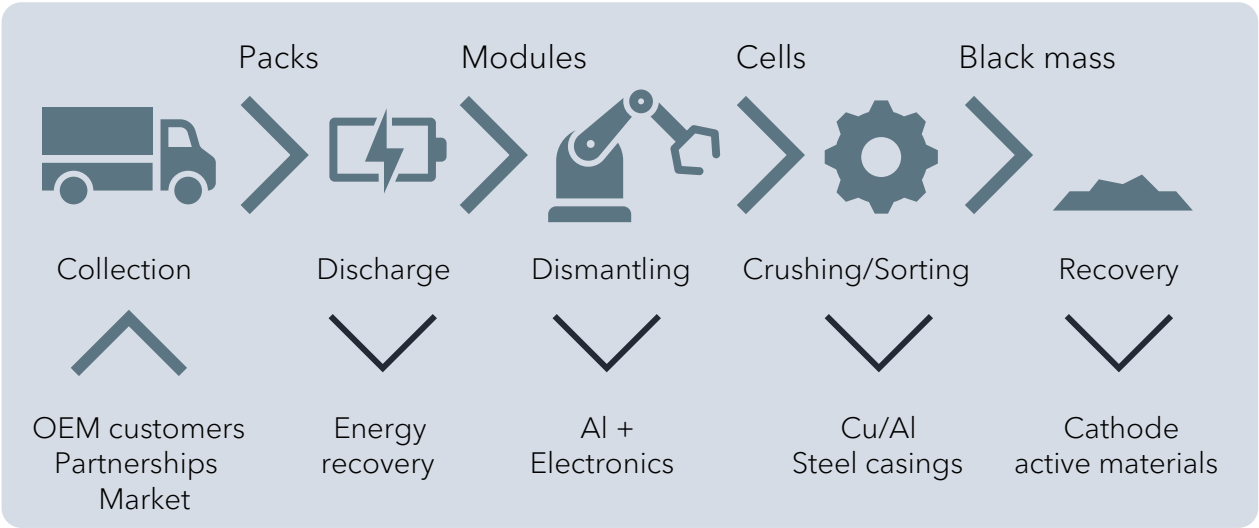


Figure 34. Possible recycling flowchart of direct recycling, adapted from (Gaines L. L., 2021a).

Recovered materials from direct recycling can be used directly to make new batteries (Gaines L. L., 2021a). This results in fewer steps and less energy required to reintroduce the materials into battery manufacturing. Direct recycling requires good mechanical pre-treatment and separation of materials, which also benefit the recycling of the other eventual fractions (Gaines L. L., 2021a). These other materials generally do not have a considerable high value, although, at least some. But another aspect is that some of these materials contain fluorine, and anything that is not recovered can end up and contaminate the following waste stream.

4.4.7 Process Comparison – Hydrometallurgy, Pyrometallurgy, Direct Recycling

Pyrometallurgy is a commonly used process, but it cannot accomplish a sustainable pathway for recycling lithium-ion batteries (Armand, et al., 2020). Pyrometallurgy can be followed by hydrometallurgy to recover some valuable materials. Still, materials such as aluminum, manganese, and lithium are still trapped in the slag product (Armand, et al., 2020). The main advantages of pyrometallurgy are that the batteries do not need to be discharged and do not need to be processed by mechanical treatment.

It is necessary to separate materials from the battery cells for all recycling strategies except for the simplest pyrometallurgy (Gaines L. , 2018). The material structure output varies between the different recycling technologies, see figure 35. In pyrometallurgy, an alloy is retrieved (which sometimes are processed through hydrometallurgy) (Gaines L. L., 2021a). The hydrometallurgical process breaks down the material structure and makes it possible to build up a new structure of choice. The demand for different cell chemistries may change in the future. It can, therefore, be beneficial to be able to rebuild material structures from scratch, which is an opportunity provided by hydrometallurgy (Gaines L. L., 2021a). Hydrometallurgy is consequently considered a future-proof approach. Direct recycling uses a different approach and focuses on maintaining the existing structures as much as possible since much value lies in the material structure. The incentive to recycle can vary depending on the battery chemistry. For example, LFP cells have a low material value. The lithium is not recovered through pyrometallurgy, and hydrometallurgy is not considered to be economically feasible due to the low-value output. On the other hand, direct recycling is a low-cost process that might be suitable for recycling LFP-cell (Gaines L. L., 2021a). One of the issues with direct recycling is that the structures wear out over time. It is currently being investigated how many times the materials may be recycled (Gaines L. L., 2021a). Another disadvantage of direct recycling is that there is no commercialized recycling solution at the time of writing (Morse, 2021).

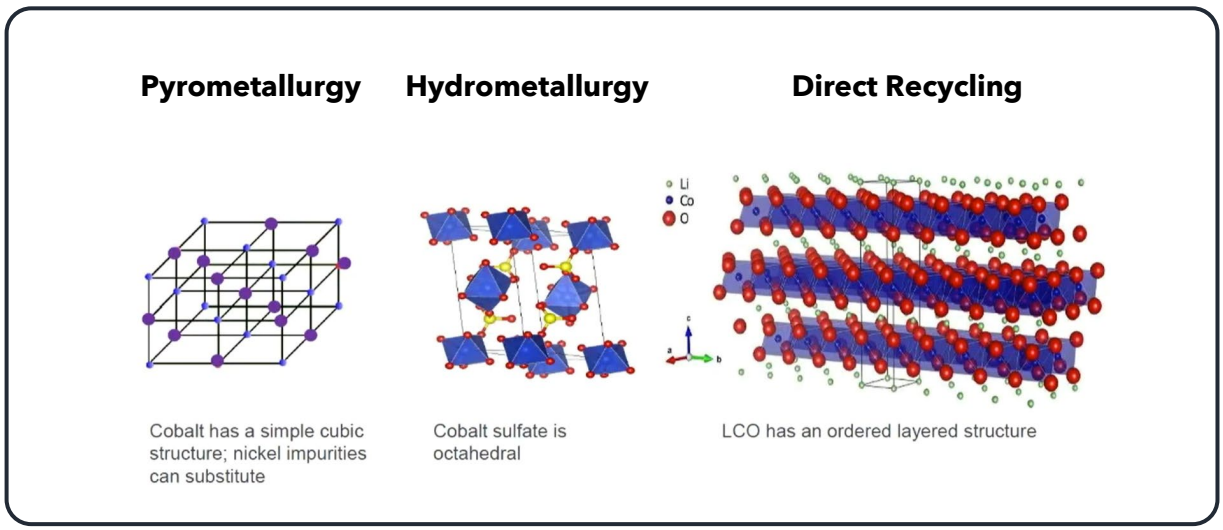


Figure 35. Materials structure output for the technologies pyrometallurgy, hydrometallurgy and direct recycling (Gaines L. L., 2021a). (Courtesy by Linda L. Gaines, 2021, Argonne National Laboratory)

When investigating sustainability, it is essential to compare the different recycling technologies' costs and environmental impacts. Figure 36 shows this context and compares the recycled materials to virgin materials based on the cell chemistry NMC (Gaines L. L., 2021a). Figure 37 compares the different cell chemistries cathode-material costs in correlation to the raw material value.

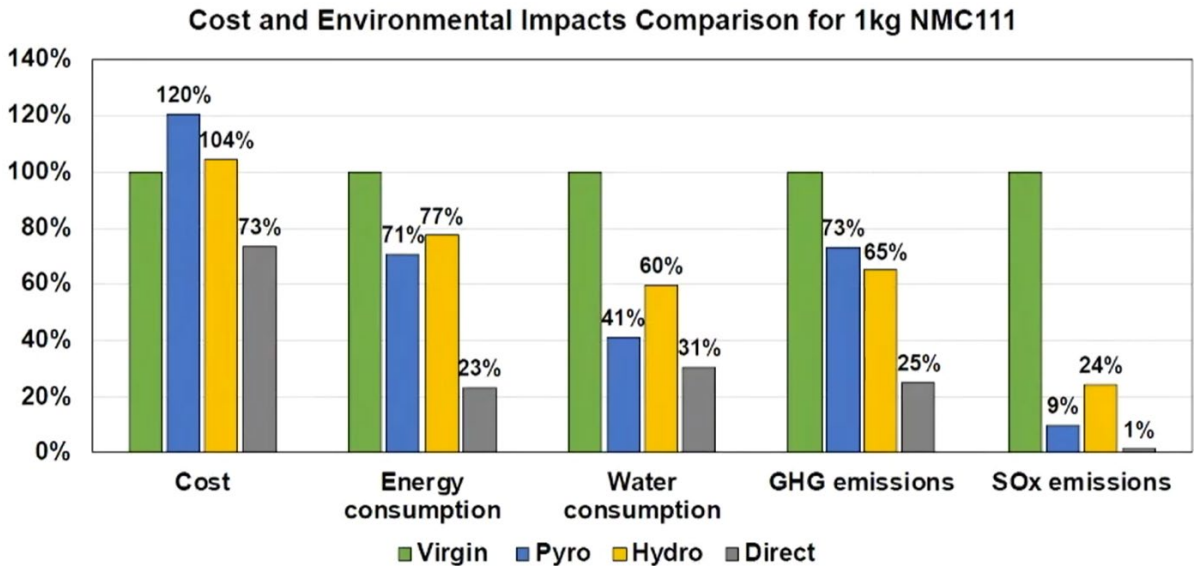


Figure 36. Cost-and Environmental Impacts Comparison – NMC (Gaines L. L., 2021a). (Courtesy by Linda L. Gaines, 2021, Argonne National Laboratory)

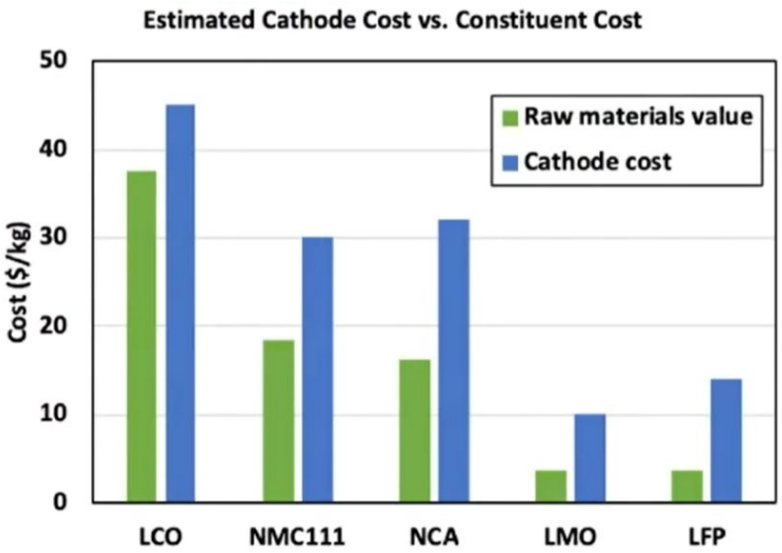


Figure 37. Cathode Cost vs. Constituent Cost, (Gaines L. L., 2021a).
(Courtesy by Linda L. Gaines, 2021, Argonne National Laboratory)

Each process has its pros and cons. Table 9 shows a comparison between the recycling strategies recovered output materials (Kushnir, 2015) (Gaines L. L., 2021a). Table 10 shows the general advantages and disadvantages of the various technologies (Kushnir, 2015) (Gaines L. L., 2021a).

Table 9. Process Comparison 1. Adopted from (Kushnir, 2015) (Gaines, Richa, & Spangenberger, 2018)

PROCESS COMPARISON 1 (BASED ON OUTPUT MATERIAL)			
RECYCLING METHOD	Ni, Co fate	Li fate	Other
Pyrometallurgy	Removable from molten alloy, 90%+	Lost in slag Max recovery approx. 50-60% (but is expensive)	Cu in alloy, The rest is lost to slag or burned for energy
Hydrometallurgy	Recovered as salts, 95%+	Can be precipitated, 90%+ recovery	Most things recoverable to 80%
Direct Recycling	Recoverable as battery materials	Partially reused, partially recovered	Other materials are recoverable as fractions, similar to hydrometallurgy.

Table 10. Process Comparison 2. Adopted from (Gaines, Richa, & Spangenberger, 2018) (Gaines L. L., 2021a).

PROCESS COMPARISON 2		
RECYCLING METHOD	ADVANTAGES	DISADVANTAGES
Pyrometallurgy	• Flexible; applicable to any battery chemistry and configuration • No sorting or other mechanical pre-treatment necessary • High recovery of metals (e.g., Co, Ni, and Cu) • Proven technology; can be implemented using existing pyrometallurgical facilities	• Cannot recycle Li, Al, or organics • Not useful for LFP • Expensive gas clean-up is required to avoid toxic air emissions • Energy intensive • Capital intensive • Further refinement is necessary to produce elemental metals from metal alloys produced in the smelting process
Hydrometallurgy	Applicable to any battery chemistry and configuration • Flexible in separation and recovery processes to target specific metals • High recovery rates (e.g., for lithium) • High purity of products (suitable for cathode precursors, etc.) • Energy efficient • No air emissions	Battery cells must be crushed (causing safety concerns) • Acid breaks down cathode structure • High volume of process effluents to be treated and recycled or disposed • Not economical for lithium iron phosphate (LFP) batteries • Anode materials (e.g., graphite and conductive additives) are not recovered • High operating cost
Direct Recycling	• Retains valuable cathode structure • Practically all battery materials can be recovered, including the anode, electrolyte, and foils • Suitable for LFP batteries • Low temperature, low energy • Can be used from prompt scraps, low volumes	•Complex mechanical pre-treatment and separations are required • Recovered material may not perform as well as virgin material or becomes obsolete by the time it is introduced to the market • Mixing cathode materials could reduce the value of the recycled product • Regeneration processes yet to be developed • Not scaled up to industrial level

4.4.8 Lithium-ion Battery Recyclers

Although recycling of LIBs is mainly adopted on the Asian continent, the number of actors increases globally. For example, Northvolt in Sweden, Lithion in Canada, and LiCyle in North America (Armand, et al., 2020) (Lambert, 2021) (Li-Cycle, 2021). The most prominent actors on the European market at the time of writing are Umicore, SNAM and Akkuser, (Leppäjoki, 2021), with respectively capacity per year as stated below:

- Umicore ca 10 000 t/year
- SNAM ca 5000 t/year
- Akkuser ca 3000 t/year

Apart from these actors, there are also many more minor actors with approximate capacities of 1000 t/year each (Leppäjoki, 2021). Though, it is difficult to estimate the market players' exact ability since these figures are sensitive information from a competition point of view. Therefore, actors are restrictive with the information they share. There may also be ambiguities in what is meant by the numbers. There are thus many obscurities. Today, there is a significant capacity shortage in the li-ion battery recycling abilities on the European market in general, with queues for some actors (Leppäjoki, 2021). There are also some uncertainties in the market as the new battery directive may affect what methods can be applied. Table 11 show general battery recycling actors in Europe.

Table 11. Battery recycling actors in Europe, adopted from (Ekberg & Petranikova, 2018) (Samarukha, 2020)

EUROPEAN RECYCLERS		
COMPANY	COUNTRY	TECHNOLOGY
Umicore	Belgium	Pyrometallurgy
SNAM	France	Pyrometallurgy and soon hydrometallurgy
Akkuser	Finland	Mechanical pretreatment & Mechanical separation
Dusenfeld	Germany	Mechanilal pretreatment, thermal pretreatment, and hydrometallurgical processing
Accurec	Germany	Mechanical processing, Thermal pretreatment & Hydrometallurgical processing
Volkswagen	Germany	Mechanical, thermodynamic drying, hydrometallurgical processing.
EDI	France	Mechanical processing, hydrometallurgical processing
Valdi	Switzerland	Pyrometallurgy
Batrec	France	Pyrometallurgiy, (calcination) Hydrometallurgical
Batrec	Switzerland	Mechanical pretreatment & Mechanical separation
Redux (big on collection)	Germany	Thermal pretreatment & Hydrometallurgical processing
Glencore	Switzerland	Pyrometallurgy
Nickelhütte (big actor on black mass, nickel and cobalt)	Germany	Pyrometallurgy
Fecupral	Slovakia	Thermal pretreatment only
Northvolt	Sweden	Hydrometallurgical processing
Accurec	Germany	Hydrometallurgical processing
Recupyl (black mass)	France	Hydrometallurgical processing
Fortum (mostly incineration)	Finland	Hydrometallurgical processing

4.4.9 Battery Collection Systems

Batteries must be collected in order to be recycled (Ekberg & Petranikova, 2018). Table 12 shows battery collection systems in different countries, which include all types of batteries. The collection of batteries are performed by several actors in separate countries and sent further to be recycled. Specifically, solutions are developed for li-ion batteries with collaborations between governments, collectors, recycling actors, and battery manufacturers, such as the collaboration between Hydro & Northvolt (Northvolt, 2021). Stena Recycling introduced a partnership during spring 2021 with Johnson Mattery to recycle li-ion batteries (Stena Recycling AB, 2021e).

Table 12. Collectors adopted by (Ekberg & Petranikova, 2018).

EUROPEAN COLLECTORS	
COUNTRY	COLLECTION SYSTEM
France	SCRELEC COREPILE
Finland	RECSER Oy
Greece	AFIS
Denmark	BatteriForeningen
Netherlands	STIBAT
Ireland	WEEE Ireland ERP
Hungary	RE'LEM
Germany	GRS
Norway	As Batteriretur Rebatt
Poland	REBA
Portugal	ECOPILHAS
Austria	UHF ERA EVA ERP CCR
Switzerland	Inobat
Sweden	El-Kretsen (Renova)
UK	G&P
Slovakia	INSA
Belgium	BEBAT
Czech Republic	ECOBAT

4.5 Li-ion in the Future

In a new project, researchers from the Chalmers Chemistry department and Uppsala University will explore the performance of recycled materials in lithium-ion batteries, together with Volvo Cars and Northvolt (Chalmers, 2021a). Much of the recovery also lies upon the very battery cell design as well. One company that has enhanced battery cell circularity is KYBURZ in Switzerland (KYBURZ, 2021). They have developed a technique where they take out the rolls from each cell to unroll them and simultaneously separate the different materials.

The field of energy storage is still evolving with new technologies coming up. One of them is the concept of "massless" energy storage (Chalmers, 2021b). A structural battery that can be a part of the product's configuration, see figure 38. The battery consists of a negative electrode made by carbon fibers and a positive electrode made by an aluminum foil coated with lithium iron phosphate. According to Leif Asp, one of the professors behind the study from Chalmers University of Technology, the recyclability of these batteries has already been considered (Asp L. , 2021). The mechanical performance is held intact whether mechanical treatment or hydro metallurgic treatment are used. The fibers might get shorter in a recycling process, and these are to be kept as intact as possible. Therefore it is relevant to investigate existing research on carbon fiber composite recycling methods for this approach.

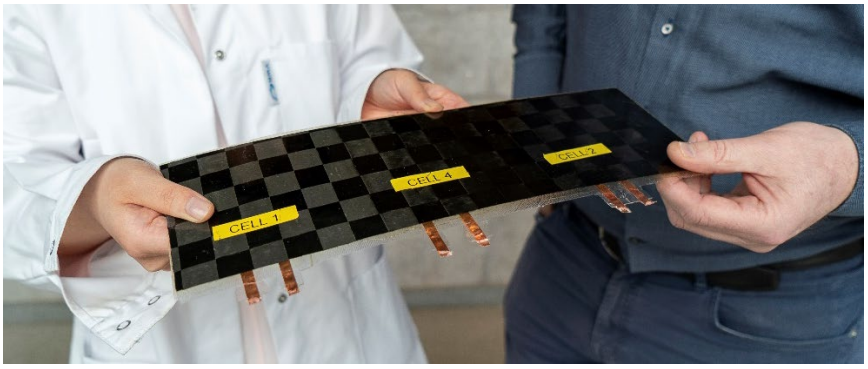


Figure 38. Structural battery. (Courtesy of Leif Asp, Chalmers University of Technology)

There are also different techniques developing. Christian Strietzel, a doctoral student at the Department of Materials Sciences at Uppsala University, is studying organic batteries (Strietzel, 2021). Some also mean that fuel cells/hydrogen may cover some of the demand on the market (Björklund, 2020).

5

VALUE CHAIN

This chapter is part of the result and provides a general overview of the lithium-ion batteries value chain by describing its whole life cycle in the context of electric vehicle applications. The activities are told in chronological order and include pathways of both so-called cradle-to-grave and cradle-to-cradle. The chapter holistically empathizes with eventual outcomes and people's doings by explaining actions and people crossing the product throughout its lifetime. The chapter has a narrative approach, occasionally expressing situations through personas to widen the perspectives.

Figure 39. Lithium-ion batteries value chain.

The lithium-ion battery value is complex and includes many activities. Figure 39 on the previous page visualize the value chain outline and the activities studied through the thesis scope. The figure also visualizes eventual shortcomings in the value chain by pink symbols and sustainable outcomes by green signs. Each activity is further described from chapter *4.1 Material Extraction* to chapter *4.15 Reintroduction*. Life cycle activities previously presented in chapter *4 COMPILATION OF INFORMATION GATHERING*, are repeated by a summary. Activities not introduced earlier are further described when appropriate for the thesis scope of lithium-ion battery recycling.

The value chain detects various obstacles to recycling which are further treated throughout the following subchapters. The significant barriers to recycling lithium-ion batteries are presented in the following summarized list:

- Collection of batteries (Ekberg & Petranikova, 2018) (Gaines L. L., 2021b).
- Complex transportation of batteries.
  - due to restrictions and safety risks (Lambert, 2021).
- Handling batteries due to safety risks (Lambert, 2021).
- Managing different cell chemistries
  - since mixing cells can damage the materials recovery process (Lambert, 2021).
- Disassembly and separation of different materials are difficult, mainly due to complex module designs (Gaines L. L., 2021b) (Harper, o.a., 2019).
  - impurities of the black mass due to insufficient material separation decrease material recovery during recycling through hydrometallurgy as well as so-called direct recycling. Impurities are residual materials of metal compounds such as copper, tin, iron, and aluminum (Petranikova, 2021) (Gaines L. L., 2021b).

5.1 Material Extraction and Refinement

Material extraction is the first step in the value chain. It is a complex topic and links to environmental, economic, and ethical aspects. In short, the extraction methods are connected to negative impacts on nature, unethical working conditions, and social factors such as conflicts. The most prominent materials in a lithium-ion battery are nickel, aluminum, lithium, and cobalt. This section describes materials of most significant concern, and the often discussed materials regarding lithium-ion batteries are lithium and cobalt.

Lithium
Globally, the largest producers of lithium are Chile (44 percent), China (39 percent), and Argentina (13 percent) (SGU, 2021a). Within the EU, there is some production in Portugal, but most of the need is met through imports, mainly from Chile (78 percent), the USA (8 percent), and Russia (4 percent). At Cínovec in the northwestern Czech Republic, on the border with Germany, there is a promising lithium prospect where the possibilities for mining are currently being investigated.

The largest lithium reserves are found in South America and China, where lithium is extracted from saltwater in salt lakes (from salt deserts) (tukes, 2021). The saltwater is

pumped up and concentrated by evaporating water, usually in large basins under the sun. The method is not considered sustainable since it (Early, 2020):

- Cause major water consumption, 469 m^3 per tonne of lithium, in addition as conducted in already water-scarce places in the world.
- The extaction method cause CO2 emissions, 5 000 kg per tonne of lithium.
- The method takes up significant parts of land, 3,124 m^2 per tonne of lithium.

Lithium is also extracted from hard rock mines such as in Australia. Hard rock mining cause scars in nature but is also related to other sustainable issues like (Early, 2020):

- Significant CO2 emissions due to usage of fossile fuels, 15 000 kg per tonne lithium.
- Water consumption, 170 m^3 per tonne of lithium.
- Use of land, 464 m^2 per tonne of lithium.

Geothermal water extraction is another method currently under development to extract lithium (Early, 2020). It is a promising method from a sustainable point of view since it causes very low CO2 emission and only uses 3 m^3 water and 1 m^2 land per tonne of lithium. Geothermal water is a hot saline solution found deep underground and is caused by naturally occurring geothermal processes. Reservoirs have been found in Europe, such as in Cornwall, England, and near the Rhine river in Germany. It has also been found in the US. Still, there seem to be a few years left before batteries are produced out of lithium from geothermal water extraction at the time of writing.

Cobalt

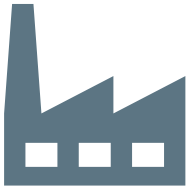
According to the EU regulation *The Conflict Minerals Regulation,* metals like tin, tungsten, tantalum, and gold are classified as conflict minerals (European Commission, 2021e). These minerals are represented in electrical products. For example, everyone who has a mobile phone in their pocket carries a small piece of Congo with them (Gad, 2013). Mobile phones contain metals such as tin, tantalum, tungsten, coltan, and gold, all of which can be related to mining in the Congo. Same as most of the precious materials in electrical devices (Karlsson I. , 2009). The Democratic Republic of Congo is a country on the African continent rich in minerals and natural resources. It is a rich country with poor people. According to Amnesty, conflicts arise over who should control the material resources. Magda Gad is a multi-award-winning war correspondent who reported from Congo in 2013, where she described how and sexual violence was used as a weapon in armed conflicts over natural resources (Gad, 2013). Magda Gad confirms that the situation has not improved at the time of writing; victims are only younger (Gad, 2021).

Cobalt is commonly discussed for lithium-ion batteries, and about 46% of the world's cobalt is used for batteries in general (SGU, 2021b). Cobalt is not classified as a conflict mineral according to the EU Conflict Minerals Regulation. However, it is argued that it should (Järeskog, 2021). About 60% of the world's cobalt comes from Congo, and it has been related to bad working conditions and child labor in artisanal mining (Amnesty, DEMOCRATIC REPUBLIC OF CONGO, 2016). Cobalt is thus linked to unethical situations, and the market is discussing how to deal with the problem. One common tactic is to search

for other solutions, such as switching the cobalt content to other alternatives in the cell chemistry or importing it from other countries. But that might also be problematic since the discouragement may itself cause harm to already vulnerable societies who rely their income on these supply chains (Järeskog, 2021). Extractions in Congo do not seem to stop anytime soon, and Amnesty encourages companies to adopt transparency and search for sustainable solutions instead of running away from the issues (Amnesty, 2021). Amnesty urges the market to demand ethical mining and encourages product design approaches that extend the product life and enable reuse and recycling. Change cannot be managed overnight. Meanwhile, the material can be traced to ensure it has been extracted safely and ethically, for example, by using blockchain. In addition, stricter demands on the extraction processes are needed and to conduct actions to stop the conflicts. Already extracted materials may be handled with respect and kept in use for as long as possible, reused, and recycled. A joint responsibility is argued by Amnesty, together as producers, consumers, and society to work actively for change.

The significant flows of the mined cobalt go from the mines in DR Congo to smelters in China (SGU, 2021b). The smelters process the cobalt further sold to battery manufacturers, mainly within the own country but also in South Korea and Japan. Batteries are sold worldwide, mainly to the electronics and automotive industries in China, Japan, South Korea, Europe, and the USA. In Europe, there are refineries for the production of cobalt in Finland, Norway, and Belgium.

5.2 Battery Cell Manufacturing



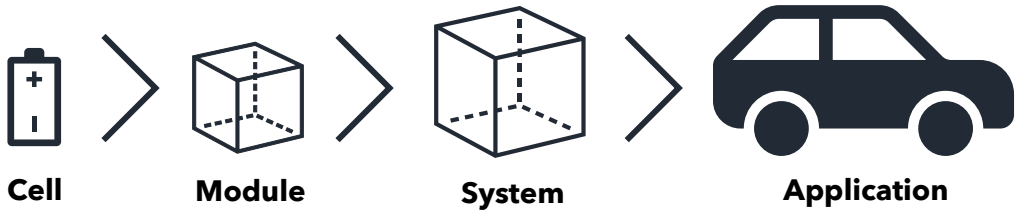
Most of the world's lithium-ion batteries are produced in Asia (Armand, et al., 2020). But battery manufacturing sites are built up or are under construction on other continents such as Europe. According to a report by IVL (Swedish Environmental Research Institute), the productions method and the energy use stand for the most emissions of lithium-ion batteries (IVL, 2019). The choice of energy resource has the most significant environmental impact. One actor who has adopted this is the Swedish battery manufacturer Northvolt who uses hydro energy to power its plants in the northern parts of Sweden (Northvolt, 2020). The energy mix used has a considerable impact on the output, and thus Northvolt claim they will produce the greenest lithium-ion batteries in 2022.

5.3 Purchase

Purchase is an essential part of ensuring materials and components. It is crucial to ensure sustainable purchase by considering sustainability covering environmental, ethical, and economic aspects. During the digital conference on sustainability Miljöstrategidagarna, Sweden, Kristin Tallbo, sustainability strategist at Adda presented strategies for sustainable purchasing methods (Tallbo, 2021). Adda is working on an open-source tool to be used as a guide to performing sustainable purchasing. It is aimed at municipalities but may also be used by medium-sized enterprises. Another open-source tool for risk assessment is the Belgium tool CSR Risk Check, also sought to be used by small and middle-sized companies. More companies are also using Blockchain to ensure sustainable purchase, such as the battery manufacturer Northvolt (Northvolt, 2020).

5.4 System Integration and Application

Batteries cells are often integrated into a specific sequence. Cells are first connected and placed in a protective box called a module (Edström, 2021). Then the modules are connected and put into another larger box, referred to as a system. Later it is usually mounted in an application of choice. The system also requires a BMS – Battery Management System to monitor and control the battery. The battery system is commonly included in an application that may be anything from an EV to a ferry to an energy storage system. The connection between the battery system, the application, and the charger must work correctly to maintain performance, extend the life, and ensure safety.



There are no standard constructions, and actors usually design their own solutions (Edström, 2021). Battery pack constructions are complex because they must withstand external stresses such as shock and vibration. Hazardous materials should be avoided in the construction correlating to current regulations described in chapter 4.2, as well as for sustainable incentives described in chapter 2. However, there are exceptions, and regulations often lag. At the same time, there may be conflicting incentives. There are specific regulations on fire safety that place significant demands on the choice of materials, such as flame retardants.

5.5 Trade Situations

There are different types of trade situations related to lithium-ion batteries. Business to business, business to customers, and rentals are the more common ones. The trade has a direct connection to the ownership. Today, OEMs (Original Equipment Manufacturer) have a so-called producer responsibility that remains as long as the battery stays in the first intended application (Swedish Environmental Protection Agency, 2020a). Still, the buyer of the application owns the battery and decides what to do with it. The producer's responsibility remains even when the application is resold. Some of the vehicles will be sold and change country during their lifetime. A significant number of electric cars have reported being shipped abroad from the country they were initially sold, often to countries like Ukraine and Russia (Melin, 2021c).

There seems to be a certain lack of knowledge among consumers, for example, regarding risks detected during interviews held during the thesis. One such example can be seen on the marine side, where more lithium batteries for small boats appear. These batteries are often adopted to be handled in marine environments with extra tightness and corrosion-proof busbars and plus/minus poles. Saltwater can be harsh against busbars and poles in combination with electricity, which accelerates corrosion. Therefore, marine applications often involve and require slightly more expensive materials. Thus, this type of battery may be more expensive. This has made some consumers buy batteries intended for other applications such as caravans (which do not have the same climate protection) and puts in a boat (Leppäjoki, 2021). This can lead to problems. In the worst case, it can cause danger. Severe corrosion of terminals may also make it difficult to discharge when it is distributed for recycling.

5.6 Maintenance

There are several types of maintenance that can be made to a lithium-ion battery system, such as software updates to change and extend functions and hardware updates. Batteries age over time, and different batteries in a system may age differently. A battery system is never better than the weakest battery in a battery configuration. Therefore, replacing the weakest module can increase the capacity of a battery system (Sundström, 2021).

5.7 EoL in Application

There can be different reasons why a battery reaches the end of life in an application. The following ist summarizes reasons to end of life in the initial application (Melin, 2021a). The second list summarizes how the ownership may change during the end-of-life scenario.

Summary of reasons to end-of-life in the application (Melin, 2021a):

- Battery upgrade
- Warranty
- Collision
- Aging

Summary of ownership change during end-of-life in the application (Melin, 2021a) (BIL Sweden, 2011) (Leppäjoki, 2021):

- Second use
  -from business to business
  -from business to customer
  -from consumer to consumer (e.g., buying and selling on online marketplaces such as Facebook Marketplace or a Swedish online marketplace called Blocket).
- OEM – Original Equipment Manufacturer
- Insurance company
- Car scrap (authorized and unauthorized)
- ATF – Authorized Treatment Facility
- Collector
- Recycler

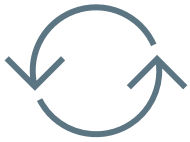
If an EV has been through a collision, the G-forces can have caused damage to the battery cells. According to an interviewee from the Swedish EV industry, the battery is often classified as scrap if the airbag has tripped. Some systems have internal safety mechanisms that are triggered simultaneously as the airbag is being deployed. For example, small controlled explosive loads can shoot off the connections to the battery. The collision activates the loads in order to disconnect the poles from the internal battery. Another way to solve the same issue is through software, which may be easier to reverse. A collision from the front or rear is ordinarily ok for the battery since the car body has taken up the main forces. But a collision from the side results in the battery taking up most forces which may damage the battery.

Depending on the situation and reason, the battery may end up in another possession. For example, the insurance company can redeem the vehicle with a battery (Melin, 2021a). Then the insurance company decides the destiny for the battery. If a private person chooses to scrap the battery, the individual person can decide what to do with it or where to hand it in. If it is handed to a car scrap, they will, in turn, determine what may happen to the battery. Today, there is a misconception about used batteries. Some people might think that batteries have a high secondhand value or high recovery value. But scrapping an EV can be expensive. Recycling an EV can cost about 20 000 - 25 000 SEK (Swedish Krona), according to Jimmy Eklind, at the Sktrotfrag group in Sweden (Regnander, 2019). According to the industry organization BIL Sweden, the commercial life of an electric

vehicle is expected to be about 17 years. Warranties are often 8 years which also can affect the situation (Melin, 2021a).

Batteries that have been exposed to heat or that have gone through a fire must be handled carefully since they can ignite spontaneously, even after the fire has been extinguished. Batteries that have gone through fire have a very low material value (Petranikova, 2021). The ignition has caused melting inside the battery structure due to the high temperatures. As a result, the materials have burned away or melted together, complicating material recovery. Therefore, there is not the same value to the materials. These cases are usually distributed directly to incineration. Everything that has been exposed to high temperatures will be put in saline for a severe time of period before it is sent for further distribution (Leppäjoki, 2021).

5.8 Repurpose



In this report, repurpose refers to when a battery is put into another use different from initially supposed. When batteries reach end-of-life in an application, they may have capacity left. These types can be put to another use (Melin, 2021a). It may be used for more minor volume-demanding applications such as energy storage systems. Despite the destination (repurpose or recycle), the battery still needs to be removed from the application. There might be some concerns of how to remove the battery system from an application, listed by (Harper, o.a., 2019) as follows:

- Variety of shapes and sizes
- Different pack configurations and locations
- Different fixings and tooling required
- Bolts and fixings can be rusted
- Heads of fixing may be rounded or sheared
- Position of bolt head not always fixed
- Vehicle bodywork may be crash damaged

In most cases, the owner of an EV owns the battery. However, the OEM (Original Equipment Manufacturer/the EV producer) still carries the responsibility through the so-called “producer responsibility” (Swedish Environmental Protection Agency, 2020a). The scope of the producer responsibility regarding lithium-ion batteries seems somewhat vague in today's regulations, and changes to the content of this regulation are discussed for the updated battery directive, which may affect the situation of reuse and recycling.

The pioneers of energy storage systems correlate with the early adopters of electric vehicles by OEMs such as Nissan, Renault, BMW, and Daimler (Melin, 2019). These companies have been involved in projects and initiatives regarding energy storage systems for industries, households, commercial premises, more extensive energy storage in regional or national electricity networks, or to support charging of electric cars in both homes and for charging stations. The OEMs have, in many of these cases, combined both used batteries and new batteries. This is because the number of batteries coming back is

small, and the demand for capacity on the market is greater than the secondary batteries may support (Melin, 2019).

The case of repurposing is argued to be one of the more promising approaches for the circularity of lithium-ion batteries. At the same time, it is also argued that reuse/repurpose will only delay recycling (Berg, 2019). Debates are ongoing on whether batteries should be reused or recycled. The promoter for recycling states that the development goes forward and that the same efficiency in batteries can be accomplished using less cobalt with today's technology. This means that the cobalt content in older batteries can suffice for more batteries, why being an argument as to why reuse delays recycling and delay access to valuable materials. Promoters for reuse state that it must be better to use a product as long as possible because of the initial cost of producing it (economic, environmental, and society) (Melin, 2021b). Recycling to produce new products from the content would also add costs to the equation, similar but not all of the initial ones. This issue is discussed in chapter 7.7 Future Work.

According to Hans Eric Melin at Circular Energy Storage, there are three ways batteries may come to be relevant for reuse (Melin, 2021a):

1. The battery fails when still warranty in force from the carmaker.
2. The application (e.g., electric vehicle) is involved in an accident involving the insurance company.
3. The owner is offered a battery update from the carmaker.

All of the examples above generate battery packs for reuse in a controlled manner. The batteries' status can be controlled methodically by authorized personnel. The batteries' history may be tracked more easily, which may become key to ensuring the quality of the reused batteries (Melin, 2021a).

The case of reuse may differ depending on the situation. In order to give a holistic view of reuse, two personas exemplify two cases as follows. The personas are presented as Camilla and Mike as follows.

Persona examples:

Camilla is working at a solar panel company with a joint venture with one of the big EV companies. They are about to build their first energy storage system of used EV batteries to power their office building. The collaboration goes excellent. She couldn't imagine the struggle if it wasn't for the joint venture. It has made it possible to access and drive the internal BMS and reach all the batteries' internal sensors correctly. The system has better control, making her feel glad that her company can provide a safe and efficient energy storage system.

Mike is an amateur technician who solves most of his problems himself. He has good experience in switching out batteries in his electrical devices, such as drills to hoverboards. However, he had a minor fire accident with the latter. He has gained knowledge by watching YouTube videos and buying secondhand items online, sometimes coming from scrap yards and individuals. He has now got the idea to build an energy storage system for his tiny house on wheels. He has a good, destined place for the tiny house already, up in the Swedish north. Everything is already set and approved by the landowner, and Mike looks forward to having a close-to-nature weekend escape. This will be his first more extensive system, but he has confidence thanks to his previous experience. How hard can it be, and what can go wrong, right?

The last example is a not too unlikely scenario. Hobbyists are harvesting battery modules from both Tesla and Nissan Leaf to build energy storage systems (Melin, 2021a). A simple search on YouTube with the search-phrase "diy energy storage systems" gave multiple results of do-it-yourself videos. The videos guide the viewer on how to build their own energy storage systems out of old lithium-ion batteries from electric vehicles and relative applications. As earlier described in chapters 4.1.4 - 4.1.7, the lithium-ion batteries' functionality and characteristics are complex. This results in a not entirely unproblematic equation, depending on the expertise of the hobbyist. There are many reasons why this is an issue. First of all, the knowledge of characteristics is essential, as well as electricity characteristics. Batteries handled wrong may be dangerous. In addition, the electricity by itself is hazardous for higher voltages. The traceability of the batteries is also a problem. People who buy secondhand batteries online from unauthorized actors might end up with a battery from an EV that has been through a collision. Or other scenarios such as overcharged or discharged to too low SoC levels. These scenarios may cause eventual changes to the battery cells' inner structure, which can lead to unexpected events making the batteries potentially dangerous. At the time of writing, the trade with second-hand lithium-ion batteries is performed between non-authorized individuals on online marketplaces, and not everyone is aware of the technical requirements and laws that apply.


This reasoning is not an argument to rally over the intention of repurposing old battery systems. Hobbyists most likely build systems out of the best intentions. Still, there are many aspects and challenges to grasp, and things can still go wrong despite the good purpose. Lithium-ion battery systems are complex. The balancing and the monitoring of the battery cells are crucial to accomplish practical and safe systems. One must know what they do to connect the system correctly, not to override any safety mechanisms. Also, it might be a challenge to use second-hand batteries since not all systems let anyone read out the data from the internal sensors in the battery pack, such as temperatures. This data can be protected through software, and the sensor can be made physically challenging to reach. There are conflicting incentives to this issue. Unauthorized people use EV batteries to build energy storage systems. If a fire occurs due to such a case, then there is a risk that the electric car company, in particular, will receive bad publicity, even though the latest installer caused the fault. Similarly, EV battery systems have been overridden by amateurs to "trim" the batteries, which has led to fires. This may give incentives for manufacturers to protect their systems more, which may become a conflicting approach to reuse and may complicate recycling. Today there are few agreements between firsthand applications (OEM's) and repurpose actors, though it is starting to be established. One example is Battery Loop, which uses Volvo batteries in energy storage systems (Volvo, 2021). But agreements between OEM's and amateurs do not appear to be happening in the near future.

The new EU battery directive suggests that OEMs shall grant access to the BMS system. According to Hans Eric Melin at Circular Energy Storage, this is a very bold move (Melin, 2020). Melin argues that the suggestion may meet considerable resistance from the OEMs. However, according to Melin, if the proposal gets adopted, it opens up for more 3rd party actors on the reuse/repurpose market.

5.9 EoL and Collection

Eventually, all batteries reach their end-of-life, where they must be recycled. The collection process differs between lithium-ion batteries from consumer products and those from EVs. For consumer products, batteries in Europe are commonly collected by collectors who are included in the EUROBAT (European Association of National Collection Schemes for Batteries) (Bergh, 2020). For EVs, the path is different. Here recyclers work in collaborations with 3rd party logistic companies who work in country-specific recycling schemes with authorized personnel.

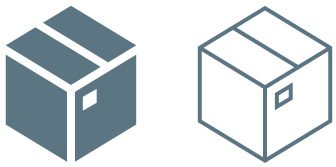
There are not many refund systems for lithium-ion batteries, but there are some examples. Toyota Prius collected their batteries through refund systems (Toyota, 2021). In Shenzhen,

China, a unique deposit-refund scheme for electric vehicle battery recycling has been tested (Li, Mu, Du, Cao, & Zhao, 2020). There are also incentives, such as the Battery Passport Services, to keep track of the batteries (Battery Passport, 2021).

EoL (end-of-life) batteries can take various pathways, and the knowledge seems to differ among the eventual people crossing lithium-ion batteries at their end of life. Some have a good understanding of the batteries' value and how to store and handle them. Others do not. For example, historically, there have been examples of scrap yards keeping batteries, believing they constituted a high value. These batteries have been seen to be stored outdoors for more extended periods, which has made connectors corrode, and the battery may also have self-discharge to such extent it has damaged the battery, which hinders eventual reuse. The misconception of the EoL batteries value has applied to various actors, from the very owners of EVs to scrap yards. EV batteries can become expensive to recycle (Regnander, 2019). In addition, transportation can also be expensive.

Lack of incentives for recycling can have negative consequences. Looking back in history, when the Berlin wall came down in 1989, a phenomenon occurred where people from the Eastern Bloc of Berlin began dumping their Trabants prior to modern west-build cars (Tompkins, 2008). The Trabant was a car manufactured in East Germany under the GDR and was made from hard plastic covers, also known as Duroplast, and a steel chassis. The motor was slow and noisy and emitted 10 times more hydrocarbons than a modern car. Altogether, these cars had very little material value. When the Trabants were dumped, they were basically ditched anywhere in streets or nature or given away for free since the cost of scrapping the car exceeded the car's value. On the 7th of October 1989, 1’600 abandoned Trabants were reported in Prague left by East German refugees (Tomforde, 2016). People sometimes act differently from what they know is best since the incentives mismatch.

5.10 Packaging and Transportation



In order to send lithium-ion batteries (and equipment containing li-ion batteries), specific regulations need to be followed according to Swedish laws (MSB, 2021). The rules state actions such as how the batteries are classified, packaged, marked, and declared. Lithium-ion batteries are class 9 dangerous goods in ADR, M4 Lithium-ion batteries (Asp A. , 2021). Cells and batteries, cells and batteries in equipment or cells and batteries packaged with equipment containing any form of lithium shall be assigned specified labeling. Lithium-ion batteries, classified as 9 dangerous goods, require special training called ADR, which relates to both the person who ships the goods and the transporter of the goods, e.g., the driver (MSB, 2021).

Transportation of lithium-ion batteries requires specific packaging, which varies depending on the particular case. EV batteries are classified as green, yellow, and red, and the classifications are based on the battery's status (Bergh, 2020). Red batteries are considered hazardous batteries and can come from crashed or burnt EVs, and these batteries need to be packed in particular safety boxes/containers. The regulations require the container to extinguish a fire, contain leakage, and filter hazardous gases. These boxes are expensive and cost about 10 000 – 25 000 EURO/container.

The yellow batteries are considered less hazardous and require less advanced packaging. These batteries are often packed in plastic or wooden boxes after being placed in a plastic bag and surrounded by fire suppressing materials such as Vermiculite or sand (Bergh, 2020). The containers are commonly transported on EU pallets.

Green batteries are considered the least hazardous and require almost no packaging. The definition of green batteries is, unfortunately, very vague (Bergh, 2020). Therefore the yellow classification shipment method is mainly adopted.

Batteries are often transported at a certain SoC level (State of Charge) of 30% due to specific regulations, and this increases safety while transporting (IATA, 2021). However, it is not always possible to discharge batteries to these levels, for example, if the battery is damaged.

5.11 Discharge

Batteries generally need to be discharged before being recycled (except for pyrometallurgy) (Ekberg & Petranikova, 2015). If batteries are not discharged, the energy left may cause ignition during the later crushing procedure through the mechanical separation. The handling and discharge are connected to risks of high voltage, electric chock, short circuits, fire, and explosions.

There is a significant variation of battery pack/module/cell designs on the market. Stena Recycling receives batteries from many areas with these variations, which was studied through a study visit at Stena Nordic Recycling Center in Halmstad in march 2021. The variation makes it difficult to standardize the process. It may also be challenging to fully discharge the battery packs due to safety mechanisms in the internal BMS (Battery Management System), which may hinder a full discharge. Other issues might also be dirty battery packs which complicate recognition, and dirt on connectors and poles can also be a problem. Corrosion on connectors and poles is another problem. If the discharge cannot be made in a controlled manner, or if the batteries are considered hazardous for any reason, there are other procedures such as immersing the batteries in saline or distilled water (Ekberg & Petranikova, 2015). This will slowly discharge the batteries.

5.12 Disassembly/Dismantling

Disassembly and dismantling of lithium-ion batteries have been reported as challenging. The following two lists summarize the main issues for disassembly/dismantling on the system and module level.

Some of the issues on the system-level (Harper, et al., 2019):

- Removal of wiring is tricky.
- Manipulation of connectors (especially where locking tabs fitted).
- High voltages until wiring loom/module links removed.
- Lack of data on module condition in many electric-vehicle batteries
- Lack of labelling and identifying marks.
- Potential fire hazards.
- Potential off gassing.

Module-level (Harper, et al., 2019):

- Sealants may be used in module manufacture (difficult to remove)
- Cells stuck together in modules with adhesives (difficult to separate)
- Components may be soldered together (difficult to separate)
- Module state may not be known

Cell-level (Harper, et al., 2019):

- Clean separation of anodes and cathodes for direct recycling is difficult.
- Very finely powdered materials present risks (nanoparticles).
- Potential for HF compounds formed from the electrolyte.
- Potential for thermal effects if cells are shorted during disassembly.
- Chemistries not always known may be proprietary.
- Additional challenges with cylindrical cells (unwinding spiral).

Glue is generally problematic, but it could be solved if the recyclers knew the melting point of glue to reach the temperature to melt the glue intentionally or to avoid it (Musavi, 2021). A datasheet of the components and joints could also help when disassembling packs and choosing methods for further treatment.

There are many EV battery solutions on the market. According to Tom Leppäjoki at Stena Nordic Recycling Center, they have received over 200 different variations of EV batteries only during the last three-years period (Leppäjoki, 2021). Most producers have their unique designs of modules and systems that are more or less challenging to disassemble due to glue and rigid joints. Some of the systems are so difficult they require specialized tools. One recent case required a similar cutter as the fire brigade uses to cut into cars. An angle grinder could have worked in other cases, but it is a bad alternative for batteries due to sparking and heat generation. When batteries are difficult to disassemble the security becomes a difficult issue. Many times, the inner construction of the system is unknown. Therefore, it is difficult to know where to cut in order to make it safe. This increases the risk of short circuits and electric chock for those who handle the batteries. This also increases the risk of cutting through a battery cell, and if that happens, it causes an inner short circuit which may lead to a thermal runaway with fire and evaporation of toxic gases.

Today, the disassembly and dismantling of battery packs are challenging and time-consuming. Thus it cost a lot of money. In addition, much of the work is conducted manually, which constitutes safety risks. In the future, it is believed that robots could handle dismantling to ensure personal safety. The significant variation and complicated solutions of today talks against this, though. At least for the system solutions on today's market.

Sometimes it is difficult to find all the batteries in a product. According to an interviewee in the Swedish EV industry, there can be more batteries in an electric vehicle besides the very system pack. There might also be batteries integrated into the seat belt tensioners, etc. If these are left when the car is further recycled, they may cause a fire. According to an

interviewee from a smaller Swedish scrapyard, it also happens that scrap yards crush EV batteries in their processes by mistake—for example, if running a hybrid car through the crusher by mistake.

5.13 Mechanical Separation

Shredding and crushing are standard methods during mechanical treatment to separate different materials into main fractions. This is often done in a particular atmospheric environment to prevent incineration. This moment may cause contamination of active battery materials from other materials and make the battery chemicals contaminate other fractions. The size of the fractions has a significant impact. Similar sizes are easier to separate in the further separation processes since they are more easily detected by the sensors (Leppäjoki, 2021). Generally, larger fractions are more simple to sort.

The size of the battery system and modules also has an impact. Size is a limiting factor regarding the capacity of the shredder, and it might vary between actors. Generally, a rectangular shape is preferred over a cubic one, with an approximate max length of 1 m (Musavi, 2021).

5.14 LIBs Recycling

Chapter 4.4, Recycling Li-ion Batteries, earlier covered this subject. The recycling strategies can be divided into pyrometallurgy, hydrometallurgy, and direct recycling. Hydrometallurgy and direct recycling are considered the more sustainable alternatives, and out of these, hydrometallurgy is envisioned as the most promising and future-proof method.

A recycler could obtain 8 dollars per kilo for NMC cells theoretically in 2020 (Melin, 2021c). The recyclers' output value will depend on the recycling process. Battery recycling includes various sequences such as mechanical separation and others described in the following subchapters. Recovered materials from lithium-ion battery recycling (depending on cell chemistry and exact recycling process) can generally be (Harper, et al., 2019):

- Aluminum
- Nickel
- Lithium
- Manganese
- Cobalt
- Graphite
- Plastics

According to Linda Gaines at Argonne National Laboratory, there are too many different physical shapes and chemistries of batteries today to ensure an efficient general recycling process (Gaines L. L., 2021a). Jean-Christophe Lambert, the Business Development Manager at Lithion, discusses the future of li-ion recycling during the Circular Economy Day webinar held by the National Institute of Standards and Technology - U.S Department of Commerce in 2021. During the webinar, Lambert presents the challenges for lithium-ion battery recycling (Lambert, 2021), to be:

- Safety (explosion and fires)
- Handle cell chemistries
- Maximize value to reduce recycling cost
- Closing the loop on strategic battery materials
- Low GHG emission
- Facing big EoL(End of Life) volumes
- Complex transportation

It is crucial to accomplish a good network before the significant battery waste volumes enter the market to cope with the demand (Lambert, 2021). Scalable solutions are also essential. Lambert points out Lithion's geographic location in Quebec as a sustainable advantage with close access to clean and cheap hydropower. It is similar to the Swedish battery manufacturer Northvolt's strategy because their factory is also located close to hydropower to supply its manufacturing with sustainable electricity from hydropower (Northvolt, 2020).

The market is moving towards lower material value content in the battery cell chemistries, such as lowering the cobalt. Concerns are raised that the lower material value decreases the incentives for recycling (Drabik & Rizos , 2018). For example, LFP and LCO cells have low material value, and depending on the recycling method, they might not be economically feasible to recycle.

5.15 Waste

Concerns have been raised on whether lithium-ion batteries may end up in landfills, but that does not seem to be the case (Melin, 2021c). Lithium-ion batteries do neither seem to be sorted incorrectly compared to other battery types in the regular sorting and recycling systems. Today lithium-ion battery materials are recycled to a certain extent, but it is expected to improve with new battery regulations and other incentives in the business. Electronics waste may end up in developing countries, which may also be a topic of consideration.

5.16 Reintroduction

The reintroduction of materials may differ depending on the recycling strategy used to recover the materials. According to the new EU battery directive, the target materials are cobalt, lithium, nickel, and manganese. Hydrometallurgy and direct recycling are the more promising recycling technologies to manage the new requirements from the regulation. Though hydrometallurgy is considered the most future-proof approach. Hydrometallurgy makes it possible to build new chemistry of choice depending on the demand (Gaines L. L., 2021a). For direct recycling, the chemistry remains and can be reintroduced in new batteries of the same type. Today recycled materials from hydrometallurgy can be reintroduced in new battery production through a mix of 50% recovered materials with 50% virgin materials (Petranikova, 2021) (Northvolt, 2021).

6

DESIGN GUIDELINES

The main outcome of the thesis is described in this chapter, which consists of several design guidelines aimed to be implemented in the development phase of lithium-ion battery packs.

The thesis hereby suggests several design guidelines to be used in the construction and development phase of lithium-ion battery packs and modules. The design guidelines aim to promote solutions that facilitate recycling at the product's end of life to accomplish circularity in the value chain. The design guidelines are based on recycling through so-called Mechanical Treatment, Hydrometallurgy, and Direct Recycling, earlier described in chapter 4.4. The primary focus is recycling through hydrometallurgy since it is considered a promising recycling strategy thanks to high recovery rates and the purity and flexibility of the output materials (Armand, et al., 2020). Altogether the design guidelines are based on the compiled information and evaluations conducted throughout the thesis process. The design guidelines were evaluated by a smaller group of experts within the Swedish lithium-ion battery industry. The design guidelines are divided into two lists; Main Design Guidelines in chapter 6.1, summarizes the aggregate data and point to the essential aspects. Comprehensive Design Guidelines in chapter 6.2, which is a more extensive and detailed list.

6.1 LIBs DfR - Main Design Guidelines

Table 13 shows the summarized guidelines which constitute the most important aspects when designing for recycling of lithium-ion battery packs. The table includes What- Why- and How-arguments to explain the problematization and the required actions. In addition, the table also suggests examples of actions. The proposals are not the only solutions and should rather be interpreted as examples of solutions. The primary information that triggered each guideline in table 13 is summarized on the next page.

Table 13. Main Design Factors for Design for Recycling of Lithium-ion batteries.

MAIN DESIGN GUIDELINES			
NO.	**FACTOR** (WHAT)	**INCENTIVES** (WHY)	(HOW)
A	**Inform and ease access to data**	Information is crucial. a) Cell chemistry must be known to avoid mixing chemistries which may hinder material recovery in recycling processes. b) Compounds should be known to address materials to destined recycling streams.	**E.g. by** *QR-code
B	**Ensure and facilitate disassembly**	a) Materials recovery increase if sorted into main fractions as quick as possible. Either manually or through mechanical treatment. b) Contamination of the black mass (from Al, Fe, Cu and Sn) interfere or hinder material recovery. c) Ensure safety.	**AVOID** * Glue * Permanent joints
C	**Use recyclable materials**	Only recyclable materials can truly accomplish circularity to benefit human, nature, and economy.	**AVOID** *Hazardous substances
D	**Ensure and facilitate discharge**	a) Discharge is often necessary step in recent and more recovery efficient recycling technologies, (hydrometallurgy and direct recycling). b) Ensure safety.	**E.g. by** *Allowing access to module level.

A. **Information and ease access to data;**

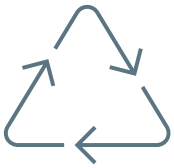
- Knowledge of cell chemistry is essential since specific chemistries cannot mix in the recycling process of hydrometallurgy and direct recycling (EUR-Lex, 2020) (Petranikova, 2021) (Leppäjoki, 2021) (Gaines L. L., 2021b) (Gaines L. L., 2021a) (Musavi, 2021) (BRWG, 2014). Mixing cell chemistry can sabotage or decrease material recovery and thus lower the quality of the output material. For example, LFP cells should not be mixed with cells such as NCA and NMC (Petranikova, 2021).
- It is more beneficial for material recovery if the materials are sent directly to each destined recycling stream since they then won't contaminate each other's fractions (Stena Recycling, 2021). It may also be helpful to know the containing materials since it makes it easier to choose an appropriate recycling method.

B. **Ensure and facilitate disassembly;**

- It is important to recycle nickel, cobalt, and lithium (Aurbach D. , 2021). As well as manganese (Armand, et al., 2020). Nickel, cobalt, manganese and lithium are considered valuable and constitute the active materials, the so-called black mass, in lithium-ion batteries.
- Aluminum, copper Iron are considered impurities that may contaminate the black mass if not removed properly and can decrease or hinder the material recovery through hydrometallurgical recycling (Petranikova, 2021). If copper fragments stay in the black mass it may still be recovered through hydrometallurgy, but it is better not to. Tin is also bad for the hydrometallurgical process.
- Polymers and graphite do not interfere with the hydrometallurgy process in general (Petranikova, 2021). Graphite may also contaminate the other fractions requiring it to be washed away (Leppäjoki, 2021).
- Mechanical separation is probably a game-changer, according to researchers within the field (Aurbach D. , 2021). The better mechanical separation, the better for hydrometallurgy (Petranikova, 2021). In addition, direct recycling mainly consists of mechanical treatment where material separation is a critical task (Gaines L. , 2018).
- A rectangular-shaped battery module may be preferred over a cubic shape, with an approximate max length of 1 meter for the mechanical separation processing (Musavi, 2021).
- After shredding, it is easier for the sensors to recognize and separate materials if they have the same size (Leppäjoki, 2021). Size has another big impact. If the parts are too small, they may be more difficult to remove (Petranikova, 2021).
- Actors request easy separation of the batteries from the application, as well as easy to dismantle from pack-level into modules (Musavi, 2021) (Leppäjoki, 2021) (BRWG, 2014) (Amnesty, 2021) (Harper, et al., 2019) (BRWG, 2014) (Lambert, 2021)(Study

visit at SNRC-Stena Nordic Recycling Center, Halmstad Sweden 2021 March).
- Lifting (Musavi, 2021) (Observation conducted from Appendix V)
- In the future robots may perform the dismantling (Petranikova, 2021).

C. **Use recyclable materials;**



- Materials chosen should be recycle-friendly and possible to circulate, and not hazardous to humans, animals, or nature (Musavi, 2021) (Stena Recycling, 2021) (RISE, 2021) (Bakker, Bocken, de Pauw, & van der Grinten, 2016) (Braungart & McDonough, 2019) (EUR-Lex, 2011) (European Commission, 2021c) (ECHA, 2021a) (European Commission, 2021b).
- Try to use materials that is already represented in the battery cell compounds (Petranikova, 2021). Recycling processes will likely be developed to be specialized on recycling these materials.

D. **Ensure and facilitate discharge.**

- Batteries may have to be discharged to be recycled through certain processes ((Ekberg & Petranikova, 2015)).
- Batteries can contain a lot of energy which also continues a safety risk. Therefore, batteries are often separated into smaller systems before they are handled. (BIL Sweden, 2011) (Leppäjoki, 2021) Study visit (BRWG, 2014) (Musavi, 2021)(Observation conducted from Appendix V)

6.2 LIBs DfR - Comprehensive Design Guidelines

Table 14. Comprehensive Design Guidelines.

DESIGN GUIDELINES (COMPREHENSIVE LIST)								
NO.	**FACTOR** (WHAT)	**DESCRIPTION/ INCENTIVE** (WHY)	**LEVEL OF IMPORTANCE** (1=least, 5=most) BASED ON EVALUATION					FACTOR= CONCLUSIONS BASED ON INFO FROM **REFERENCES:**
1.0	**GENERAL**							
1.1	Know Why & How	• Knowledge of incentives (Why), and strategies (How), to make DfR happen. Who: -Leaders to substantiate work. -Purchase/R&D as setting the level.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Corvellec, 2020) (Laestadius, 2021) (Domeij, 2021)
1.2	Prior modular design of modules	• Enable selectively switching out modules in systems, to be sent for recycling at EoL. • Replacing the weakest module improves the capacity in the remaining system. • Can facilitate transport, since separated modules don't require expensive custom size containers.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(BRWG, 2014) (Sundström, 2021) (Melin, 2019)
2.0	**MARKING**							
2.1	Use recyclable marking	• Readable for humans and machines. • Aims to keep down the number of materials. • E.g: include in design as insert in mold-, punch- or stamp- tool; Laser; Mechanical stamp.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Study visit at SNRC - Stena Nordic Recycling Center, Halmstad Sweden, March 2021)

3.0	**MARKING CONTENT**							
3.1	Cell chemistry	Clearly marked physically on modules and systems. • To avoid cell chemistries getting mixed in the recycling process since it can seriously damage the material recovery of the black mass compounds.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☒	(EUR-Lex, 2020) (Petranikova, 2021) (Leppäjoki, 2021) (Gaines L. L., 2021b) (Gaines L. L., 2021a) (Musavi, 2021) (BRWG, 2014)
3.2	Mark each different material	• State type to enable pre-sorting into different recycling streams. Make readable for humans and machines. • Pre-sort promote more efficient recycling • Not used much today but enable pre-sorting and can ease it= future-proof.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Sjöblom, 2021) (BRWG, 2014)
4.0	**QR CODE**							
4.1	QR CODE	• Refer to a link=easy to adjust info, and link further.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☒	(EUR-Lex, 2020)
4.2	Cell type (QR content)	(Cylindric/prismatic/pouch) • Different types can act different in the recycling process.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(EUR-Lex, 2020) (Petranikova, 2021)
4.3	Historic data (QR content)	• Serial number based for traceability.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(EUR-Lex, 2020)
4.4	Materials List (QR content)	• Facilitate selection of recycling strategy. • Hints material value and motivates disassembly.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(EUR-Lex, 2020) (Leppäjoki, 2021)

4.5	Recycling info (QR content)	• Inform how to act and distribute related safety info. • Reduce barriers for recycling.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(EUR-Lex, 2020) (Amnesty, 2021) (Melin, 2019)
5.0	**SAFE HANDLING**							
5.1	Mark high voltage joints	• Use colorful orange cables, equivalent to used in EV applications.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(BIL Sweden, 2011) (Study visit at SNRC - Stena Nordic Recycling Center, Halmstad Sweden, March 2021)
5.2	60 V separation steps	• Allow easy and safe separation of system into lower voltage sections.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(BRWG, 2014) (BIL Sweden, 2011)
5.3	No protruding terminals	• On modules to avoid short circuit and electric chock.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Study visit at SNRC - Stena Nordic Recycling Center, Halmstad Sweden, March 2021)
5.4	Consider Poke-yoke solutions	• E.g. a system must be separated into lower voltage sections to make modules movable or to reach other connection points. To ensure safety.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Conducted observation in Appendix V - *LIBs Recycling* and in chapter 3.1.5 -*LIBs Recycling*; - *Tesla Teardown* and - *Robot Dismantling*)
5.5	Enable easy lifting	• Provide handles and/or attachment points. • Place to avoid short circuit/electric chock. • Consider ergonomics, designing modules to be lifted manually. Prior 15 kg max. • Place for easy access for both human and machine.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Musavi, 2021) (Conducted observations: Appendix V, and in chapter 3.1.5 -*LIBs Recycling*; - *Tesla Teardown* and - *Robot Dismantling*)

6.0	DISCHARGE							
6.1	From system level (Prio 1)	• Safer as the internal BMS and the internal sensors are used.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Leppäjoki, 2021) (Study visit at SNRC - Stena Nordic Recycling Center, March 2021)
6.2	From module level (Prio 2)	• Make terminals easy to access and connect. • Design to avoid corrosion and dirt. • Provide discharge info.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Leppäjoki, 2021) (Study visit at SNRC - Stena Nordic Recycling Center, March 2021)
6.3	As last resort	E.g. if or hazardous cases, broken welds/ bond wires of cells. • Enable handles/ attachments to be used to safely immerse system/module in liquid. e.g. saline. • Make sure liquid reaches batteries. • Select salinity to accomplish conductivity to discharge by ≤0,05 C, to ensure safety (Sjöblom, 2021). • Saline do not affect black mass recovery via hydrometallurgy (Petranikova, 2021). • Saline cause less valuable final products in Direct Recycling, but it is safer and may be the way to go for severely damaged cells (Gaines L. L., 2021b).	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Petranikova, 2021) (Leppäjoki, 2021) (Musavi, 2021) (Sjöblom, 2021) (Gaines L. L., 2021b)
8.0	DISS-ASSEMBLY							
8.1	Separation of system from application	• Sectioning into safer voltages.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(BRWG, 2014) (BIL Sweden, 2011)

8.2	Separation into single modules	• Recycling and shredders can handle limited sizes. Preferably below 1 meter. A rectangular shape with thickness is preferred over a cubic shape.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Musavi, 2021)
8.3	Separation into main fractions	• Enable pre-separation of the module into PCBs; electronics; metals plastics and batteries, to be sorted into each destined recycling stream. • separated before shredding avoid contamination between fractions to improve material recovery.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Petranikova, 2021) (Leppäjoki, 2021) (BRWG, 2014)
8.4	Prior separation of metals, electronics, PCBs	If separation is restricted, prior to separate: • Metals: mixed in the black mass, e.g. iron and aluminium, can hinder recovery in hydromet. • PCB/electronics: contain tin which is bad for hydromet.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☒	(Petranikova, 2021) (Leppäjoki, 2021)
8.5	If materials cannot be separated	• Ensure different materials will be separated through shredding.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Stena Recycling, 2021)
8.6	Use minimum number of fasteners per module	• Few steps=incentive to disassemble (time/cost/revenue)	1 ☐	2 ☐	3 ☒	4 ☐	5 ☐	(BRWG, 2014) (Amnesty, 2021)
8.7	Use same type and size of fasteners	• Limit tools required	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(BRWG, 2014) (Amnesty, 2021)
8.8	Prior snap locks & screws	• Avoid permanent joints	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(BRWG, 2014) (Stena Recycling, 2021)

8.9	Design for automation	• Make joints reachable and discountable from the same axis as much as possible. • Work with high contrast to ease detection of joints, gripping area, etc.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Petranikova, 2021)
9.0	**MATERIAL SELECTION**							
9.1	Same as in the battery cell	• Chose already present materials to keep down the total number of materials.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Petranikova, 2021)
9.2	Green PCBs	• Use the general green color for PCBs, since many recycling facilitates detects and sorts the by its typical green color.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Stena Metall, 2015) (Leppäjoki, 2021)
10.0	**ADHESIVES**							
10.1	Avoid adhesives, thermosets and potting	• Mechanically hinders recycling. • Common compound can interfere recovery, such as thermal pre-treatment hydrofluoric acid (which is corrosive). • If adhesives are used melting temperatures should be stated, (to reach or avoid). Glues that can be be dissolved with ordinary solvents may also be considered.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Petranikova, 2021) (Stena Recycling, 2021) (BRWG, 2014) (Musavi, 2021)
11.0	**OTHER**							
11.1	Reuse or recycle? *Further explained in appendix 1.	• This is a gray zone difficult to assess. • An objective evaluation system, stating best practice per case should be developed. As an internal or centralized solution. Preferably accessed by QR.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	(Petranikova, 2021) (Berg, 2019)

7

DISCUSSION

The following chapter discusses the thesis elements, such as the general topic, the theoretical framework, the methods and process used, the results, and the various findings. In addition, the chapter also answers the research questions and discusses the research contributions. Lastly, it considers potential further work.

7.1 The Topic at Large

There has been much discussion about electric cars and how sustainable they are compared to combustion engines and fossil fuels in recent years. When problems about EVs are highlighted, it may be easy to use this to propagate against lithium-ion batteries. There might be actors that would benefit from spreading this type of information. The Danish documentary *The Campaign Against the Climate* by Mads Ellesøe asserts that actors in the oil industry employ fake researchers to write dissertations to create confusion (Ellesøe, 2020) (DR Sales, 2020). Therefore, it should be made clear that any comparison should be performed in a methodical, objective, and constructive manner. All aspects should be clarified and set against each other, and such has already been done. The electric vehicle manufacturer Polestar presented their LCA Report for Polestar 2 by comparing it to a Volvo XC40 (Polestar, 2020), parts of the result presented in figure 6.1. Comparisons have also been conducted by Bengt Steen and Helena Berg in their report *Integrated sustainability assessment of tomorrow's battery concepts* for the Swedish Energy Agency (Berg & Steen, 2017). Their calculations are based on LCIA, which not only address the CO2 but also the ethical aspects.

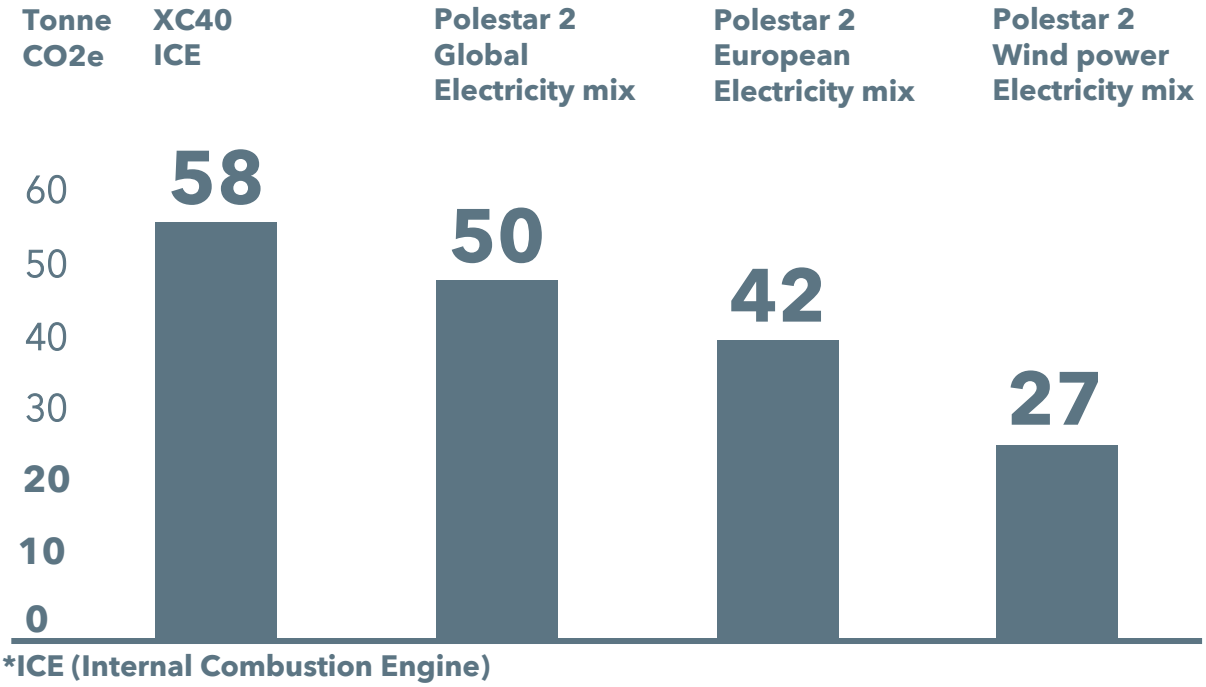


Figure 40. Polestar 2 LCA Report - CO2 from material production, li-ion battery modules (only Polestar 2), manufacturing, use phase and end-of-life. Adopted by (Polestar, 2020).

7.2 Theory

Although circular design is a very hot and hyped topic, it may also be considered quit messy. The same applies to design for recycling. There are several guides that cover different topics, but there does not seem to be one that covers everything in one place. This of course makes it much more difficult to work with the area in general. There is a plethora of circular tools, and it seems to be popping up at a faster pace in recent years. Nordic roadmap and Disruptive design are some examples of guidelines and approaches. It can be argued that many available choices are good because then there might be something that suit everyone. But with more choices, it also becomes more difficult to choose. It can therefore be difficult for companies to start their circular journey because it is hard to know where to start and what method to adopt. Therefore, the efforts made within the EU with the Green Deal are good for giving an overall picture. There will also be more standards in the field, which can be seen by conducting a simple search on SIS, SIS standards. One way to tackle the issue has in this study been to discuss with experts, researchers, and actors.

The EU Green Deal and the new taxonomy puts up ambitious goals. However, there are also critics on the deal that EU is considered as an isolated island, which is discussed through a chronicle by Sven Lindström, CEO at Midsummer (Lindström, 2021). Lindström claims that EU imports CO2 emissions through trade and that most of the global emissions can be derived to the Asia continent. He, therefore, questions whether decreasing emissions in the EU will be effective. Solar panels can be produced in Asia with electricity from charcoal-powered plants, shipped all over the globe, and toll-freely enter the European market. While panels produced by green electricity in Sweden are penalized through taxes. Lindström claims that this is counterproductive for the climate and that the EU should work on these business and trade policy issues.

It is problematic when leaders put up goals in the far future because they will not be held responsible for them, argues Lindström. He also suggests that goals should be supplemented with intermediate goals that are followed up and measured during the decision-makers' term of office. This type of reasoning is also brought up by the professors in in business economics Hevré Corvellec, at Lund University, and Staffan Laestadius, Professor in industrial development at KTH (Corvellec, 2020) (Laestadius, 2021).

The thesis's primary focus is design for recycling. Simultaneously, it is critical to be aware of the whole product life cycle and its activities so that the design solutions do not aggravate the situation elsewhere, neither earlier nor later in the value chain. The holistic view minimizes the risk of suboptimization. By knowing the value chain steps, it is possible to act on them and create designs that facilitate recycling at various life cycle stages, such as promoting the collection of batteries vital for recycling. Thus the overall picture opens up to design products with increased customer satisfaction throughout the whole lifespan. Circular design has the potential to create value and profit margins for companies who adopt the methods. Circular design methods may also be equated as having an expert in resource efficiency onboard the development team. Not so surprisingly there are many connections between design for recycling and lean production. At Stena Recyclings website it is presented as Green Lean by focusing on the lean of waste in relation to design for recycling (Zarah Zättlin, 2021). Stena Recycling target waste reduction but there are even more lean-factors that can be used in design for recycling.

7.3 Method

The area is vast, and it wasn't easy to delimit. Delimitation, therefore, became an iterative process throughout the work. It was crucial to gain a comprehensive understanding of the topic. This made the information phase central to other parts. Figure 41 visualizes the thesis input content and the outcome.

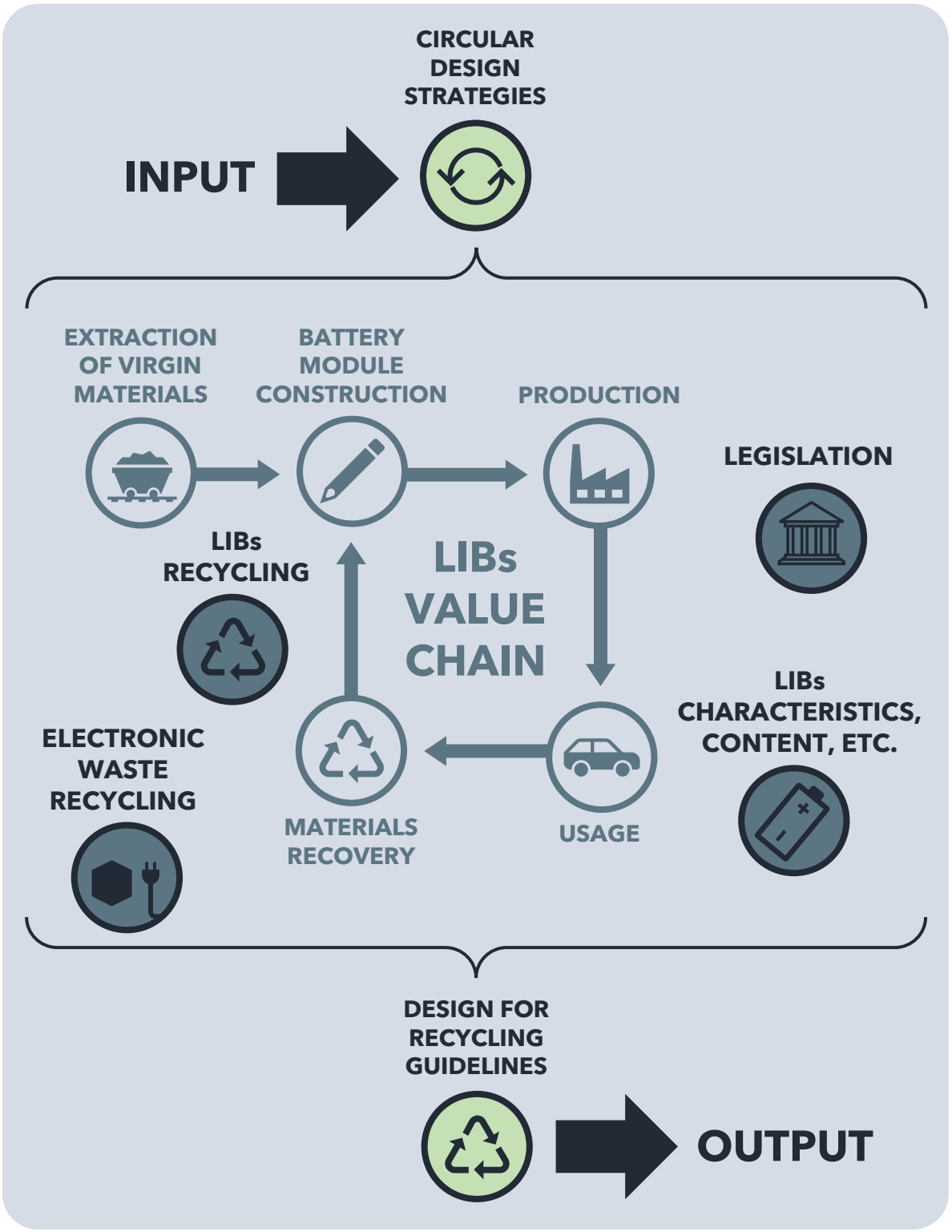


Figure 41. Thesis content overview.

The results of the thesis are the compiled information in chapter 4, the value chain roadmap in chapter 5, and the design guidelines in chapter 6. The compiled information consists of various topics, visualized in figure 41. It is relevant to the scope since the addressed issue is interdisciplinary, which includes many different professions, and interdisciplinary collaborations will be crucial to cope with the challenges of lithium-ion battery recycling.

7.3.1 Value chain mapping and information gathering

The value chain has been central to gain empathy for the steps and people crossing the product throughout its lifetime. Various methods have been used to gather the information, such as literature review, new's screening, interviews, observations, and attending webinars. The variation of methods has contributed to a broader perspective.

As of 2021 and the Covid-19 pandemic, most events were held digitally during 2020 and 2021. This has possibly resulted in more accessible information online, which contributed to the investigation.

An interesting finding during the thesis was the importance of symbols. Visualization worked as a tool for communicating the value chains complex systems and symbols were used prior to text. This gave a quick and increased understanding of the viewer/reader. It has been proved that it is faster and easier for the brain to understand symbols over words (Shaw, 2016).

The main focus of the investigation was the Swedish and European markets. Interviews have been held prior with Swedish actors in the lithium-ion industry. It is possible that the outcome had been different if the focus were different. On the other hand, sources from outside Europe have been used, such as webinars from the U.S and interviews with researchers from the U.S and Israel, which may contribute to a more nuanced result.

7.3.2 Workshop

The workshop was held within Micropower Sweden AB and included different professions within the company. The workshop was limited to one company which may restrict the output. Still, the participants had different disciplines, which may widen the perspectives. Thus the limitation fitted in the thesis scope.

7.3.3 Evaluation

The evaluation of design factors was conducted through a small number of people within the Swedish lithium-ion industry. The review consisted of a significant number of factors (37) that constituted a risk of people losing energy while answering as they processed a large amount of information. This resulted in a chance that the latter questions were responded to more casually than the first ones. This can be seen in the answers in Appendix VII, where the response rate decreases for the last questions in the survey. The statements next to the factors constituted a risk factor since it could affect the respondent too much to steer their answers. This could become a problem if the respondents lack knowledge. However, the selection of respondents was based on their expertise within the field. This may decrease the risk and increase the conditions for the respondents to answer objectively when evaluating the factors and statements. It is also possible to argue that people in these professions have an interest in the subject, which is why they are more

receptive to the amount of information as it interests them. In the response message, comments were added such as "it was interesting to assess this survey." The survey was followed up with each respondent. This was important to ensure the value of the survey results.

Some of the results were established from inspiration from other actors, like the USAB, Amnesty, and “Delegationen för Circulär Ekonomi.” It was interesting to weigh already existing factors, both between factors from different sources as well as factors that emerged from research in the project.

7.3.4 Presentation of Results

Storytelling is used to describe parts of the value chain in chapter 5. Storytelling and personas are commonplace design tools often used to create empathy for a design challenge in order to develop suitable and practical solutions. In this case, the design tools are used to describe technical topics. It is perhaps an unusual strategy in the subject field of batteries. Still, it is a style choice chosen to increase understanding and facilitate empathy for different situations throughout the life cycle. Diverse actors from various disciplines influence the product throughout its lifetime, and widespread knowledge might be essential to fulfill a closed loop of the value chain. Storytelling is one of the oldest and most pervasive strategies used since ancient times to create empathy and understanding through stories.

The design guidelines are presented with a summarized list and in a more detailed list in chapter 6. The summary creates an overview of the most important aspects and distributes the information to be processed more easily by the reader. The comprehensive list gives a more in-depth source of information.

7.4 Answering the Research Question

Research Questions Phase 1.0

RQ1.1: How is recycling achieved today for the most common lithium batteries from larger applications as vehicles, and how is it expected to occur in the future?

ANSWER: Today, the main Li-ion battery recycling strategies are pyrometallurgy, hydrometallurgy, and direct recycling (the latter two are used together with mechanical pretreatment, among others). Pyrometallurgy is the most common strategy and is taking up the majority of today's waste volumes. However, pyrometallurgy is expected to be sidelined due to expected emission charges and lower recovery rates, which is considered insufficient in the updated EU Battery Directive, which proposes stricter regulations. The most promising technologies are hydrometallurgy and direct recycling. Both come with respectively advantages and disadvantages. Hydrometallurgy is the more progressive approach. Research is ongoing regarding Direct recycling. When used right, both strategies may achieve high material recovery rates from most to all materials.

a) Who are the biggest actors in recycling today, and who are expected to be so in the future?

ANSWER: The absolute most significant player on the European market is Umicore, which mainly uses pyrometallurgy. The market conditions change with the new EU Battery Directive, and the future will show which players hold and which methods are adapted and developed. Battery manufacturers such as Northvolt are starting to build their recycling methods to supply their manufacturing with raw materials, both from waste from their production processes and end-of-life batteries. New recycling actors enter the li-ion battery recycling industry simultaneously.

b) Do the needs differ between different recycling actors?

ANSWER: The need differs between recycling strategies rather than actors. The requirements thus vary between pyrometallurgy, hydrometallurgy, and direct recycling.

RQ1.2: What factors are central to facilitate and enable the recycling of lithium-ion batteries?

ANSWER: Both hydrometallurgy and Direct recycling place demands on discharge, disassembly, and reasonable material separation through mechanical pre-treatment as well as thermal pre-treatment. Both strategies also have requirements regarding the input of cell chemistries. Several battery chemistries cannot mix since they interfere or hinder material recovery through certain processes. It is possible to mix specific cell chemistries in hydrometallurgy, while other mixes may mess up the whole process. In general, it is not possible to mix cell chemistries in Direct recycling since the input also comes out as output of active material ready to use in battery production. Pyrometallurgy has the lowest requirements. It involves incineration, and a lot of materials are smelted together regardless. In

addition, batteries do not need to be discharged for pyrometallurgy. Charged batteries are an advantage in pyrometallurgy since less energy is required to generate heat for the smelting process.

a) From a broad perspective, what factors are linked to transport, handling, disassembly, and the recycling strategy?
ANSWER: It is essential to have an understanding of the value chain and the product life cycle in order to not sub-optimize.

Transport: Battery collection is the first crucial step for the recycling chain, and therefore, a well-functioning collection system is required. Transportation is also vital; it can be extremely expensive depending on the battery's condition. It is safer to transport discharged batteries, and therefore, discharge should be easy and secure. The discharge is also vital for the later stages of some recycling strategies.

Handling: Hazardous electrical connections should be marked for personal safety. The possibility of disconnecting the system into less dangerous voltage levels (e.g., 60 V) should be possible to perform safely and straightforwardly. Batteries from EVs are often large and heavy. Therefore a lifting function/device can thus facilitate handling.

Disassembly: Disassembly is a major part conducted at the recycling facilities. It is difficult and time-consuming by requiring many operations. Battery information should be easily accessible to choose an appropriate recycling strategy. The information may include the material content such as cell chemistry and other materials.

Recycling: Pre-separation of materials (through mechanical treatment) is essential as well as knowledge of battery compounds. Mixing cell chemistries into the processes of hydrometallurgy and direct recycling decrease material recovery or even sabotage it. Contamination from iron, copper, aluminum, and tin may also decrease the quality of the output materials from hydrometallurgy.

b) From a narrower perspective, are there determining aspects of form factors and cell chemistry linked to recycling?
ANSWER: Different cell chemistries are more or less suitable for different recycling strategies. Knowledge of cell chemistry is essential when choosing an appropriate recycling method and not risking mixing cell chemistries, which can negatively affect the recovery rate. A rectangular shape is preferred over a cubic one and a total max length of 1 meter is requested.

Research Questions Phase 2.0

RQ2.1: How can a battery pack be designed to facilitate the recycling of lithium-ion batteries? Based on the knowledge gained during Phase 1 and the sustainability aspects of eco-friendliness, ethicality, and economy.
ANSWER: The battery module construction should allow materials separation for distribution to the respectively destined recycling stream to enable efficient material recovery to accomplish circularity. The material selection should be based on recyclable materials.

7.5 Contributions

The thesis contributes to research by combining circular design methodologies (design for recycling in particular) and the lithium-ion battery value chain. It has collected facilitating factors for recycling from different sources to compile them in one place and has evaluated their relevance. The thesis describes why design for recycling can be beneficial from an economic point of view as well as social and environmental. It also explains why and how design-for-recycling may be applied in the design stage to accomplish effective recycling and material recovery of lithium-ion battery pack solutions. The thesis doesn't cover all aspects of this broad topic, and that was neither the intention. Nevertheless, it may provide a starting point for continued work based on the current situation. Conditions may also change over time, which is why revisions may be needed in the future.

7.6 Future Work

This thesis suggests future investigations such as discovering the value chain and the design guidelines iteratively. It also suggests an analysis of reuse and recycling.

7.6.1 Continue to investigate the value chain and the design factors

The lithium-ion industry is still young and constantly evolving. Therefore the conditions may change why both the value chain and design factors need to be updated to fit with current prerequisites. Both the value chain and the list of design strategies should therefore be seen as dynamic documents to be revised and possibly extended as new discoveries are made in this area.

The pathway of the value chain also varies depending on the studied company and actors in the value chain. It is important to be aware of the own value chain route to face the shortcomings both upstream and downstream. No matter where the actors are in the value chain, one should be aware of their own location and their possible impact and responsibility. It is possible to go more in-depth about each phase of the value chain, and by doing so, one will most likely detect more constraints to be considered.

7.6.2 Evaluation system - “Recycling/Reuse?”

There are ongoing debates whether reuse or recycle is the more sustainable alternative (Berg, 2019). This question should be answered in a systematic manner. Therefore a centralized objective assessment system is needed. It should be based on actual data calculated on all the pillars of sustainability; -nature, -social and -economic. It is reasonable to propose the method of LCIA (Life Cycle Impact Assessment) for such investigation (Steen, 2016). Unlike a pure LCA (Life Cycle Assessment), in addition to CO2, the LCIA also consider other aspects such as ethics which give a more holistic viewpoint to the issue.

8

CONCLUSION

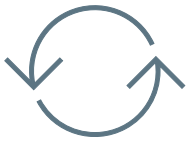
This chapter summarizes the fundamental discoveries made during the thesis in relation to the thesis aim and discusses them from a broader perspective.

It is challenging to recycle lithium-ion battery packs from electric vehicles today, mainly due to the design of battery packs and the physical integration in the application. Several aspects come into play, but the most crucial aggravating factors for recycling are:

- Collection of batteries
- Transportation
- Handling
- Managing different cell chemistries since they cannot mix
- Disassembly and separation of materials
  - Especially impurities of the black mass, due to insufficient separation of materials, which interfere with material recovery.

Several design features in today's battery designs hinder recycling. First of all, the cells contain many different materials in complex geometry. The battery cells are grouped into modules, which are grouped into a battery system, including a complex electronic battery management system and likely cooling systems. Cells differ in size and shape. Module designs also vary. Ideally, recycling could be made much simpler if all the packs and modules were similar, enabling the construction of automated disassembly lines to separate the input stream into objects of a size suitable for further processing. Similarly, standardization of cell designs would facilitate sorting and possibly enable cell disassembly instead of size reduction. Unfortunately, the trend goes towards unique and proprietary designs, especially for module designs. The cell designs use some standard measures, but different designs are also common. Other factors that may be challenging are unexpected costs for both transportation and recycling. Changing ownerships, changing responsibilities, and abroad shipping of products throughout its life makes it challenging to keep track of the batteries.

This master thesis aims to promote the circularity of the lithium-ion batteries value chain by facilitating recycling to reduce environmental impacts and minimize the value-loss at the end-of-life. Therefore, the thesis has collected enabling factors for recycling lithium-ion batteries and compiled them into design guidelines for the design phase, represented in chapter 6. The thesis suggests that circular design and design for recycling methods are beneficial from an economic point of view as well as social and environmental. The thesis has detected several incentives to implement design for recycling during the development phase of battery pack modules, such as:



- Recycling is not the only topic to consider when designing sustainable battery pack solutions. The use phase of lithium-ion batteries is of the utmost importance where functionality and robustness are essential to extend the lifetime and enable reuse. However, no matter what, all batteries will eventually reach the end of life, where they must be recycled.

- So-called circular models are preferred over linear models from a sustainable point of view. In circular models, the value is obtained, reused, and recovered iteratively. Recyclability is a vital component to accomplish circularity.

- Early design implementation of circular strategies is more cost-effective and less time-consuming, especially since it might be required later anyway due to forthcoming stricter legislation and bans on materials. Early implementation could even be essential to facilitate and accomplish recyclability at all.

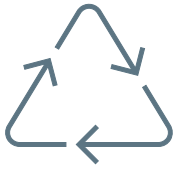
- An overall picture of the product life cycle is essential to gain knowledge to not sub-optimize when designing and constructing solutions.

- Material separation is essential in order to send the different materials to each destined recycling stream to accomplish efficient material recovery. Not only for battery-specific materials but all materials used in the battery pack construction. There are different strategies to recycle lithium-ion batteries, and they may be more or less suitable depending on the situation and material contents. However, they can all benefit from being able to separate materials easily. The separation is also essential since eventual impurities may decrease the material recovery. Some materials are especially disturbing for lithium-ion battery recycling through hydrometallurgy, such as iron, copper, aluminum, and tin. A design strategy may be to either limit these materials in the design or enable separation if used. Another idea may be to implement materials already present in the battery cell content, as lithium-ion battery recycling facilities may already be specialized in separating just these materials.

- 80% of the environmental impact can be decided during the design stage (Circular Sweden, 2021), which gives an excellent opportunity to develop sustainable products.

- Lithium-ion batteries have the overall potential to decrease greenhouse gas emissions when electric vehicles are chosen over conventional combustion engines and fossil fuels. In order to stay true to the mission, sustainable alternatives should be promoted throughout the battery life cycle from extraction of materials to transportation, production, usage, and recycling, for example, by using green electricity and ensure material recovery.

- Although cobalt content relates to ethical issues in countries like DRC, Amnesty International encourages actors to take action instead of running away from the problems. Amnesty considers targeted actions to be a far more sustainable solution in the long run, since mining in DRC does not seem to stop anytime soon.



- Design for recycling has great potential since it increases material recovery, potentially increasing profit for the recyclers. Thus, it may give the product a higher material value at the product's end of life.

- Recycled materials generally have lower environmental impacts compared to virgin materials (raw materials). Therefore, recycled materials lower the environmental impact when they are used in new products. Recycled material may therefore also be considered in the initial design. Still, it should simultaneously not interfere or be toxic to human, animals, or the nature. Less bad is not good enough.

- Actions made to facilitate recycling may also contribute to benefits elsewhere in the value chain. For example, safety actions such as separation into lower voltages are beneficial for end-of-life handling and the initial mounting, maintenance, and eventual reuse. Altogether circularity and design for recycling can trigger solutions in the design phase that increase profits and product quality throughout the whole life cycle.

- Choosing sustainable, recyclable materials and designing recyclable construction is key to accomplish true circularity. Less bad is not good enough since it will still impact the situation negatively.

- A critical component to aspect regarding circularity implementation is leadership. For circular models to be realized at all, it is necessary that it is initiated and understood by decision-makers through organizations. There will be no implementation of circular methods unless organizations understand why.

There are severe problems with recycling lithium-ion batteries of today's module constructions which prevent material recovery. Therefore, a changed approach and actions are required now, not later. Otherwise, the issues are only pushed into the future. It is a boomerang effect that will eventually come back.
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APPENDIX

Appendix I
– Chemistry/type/characteristics/application

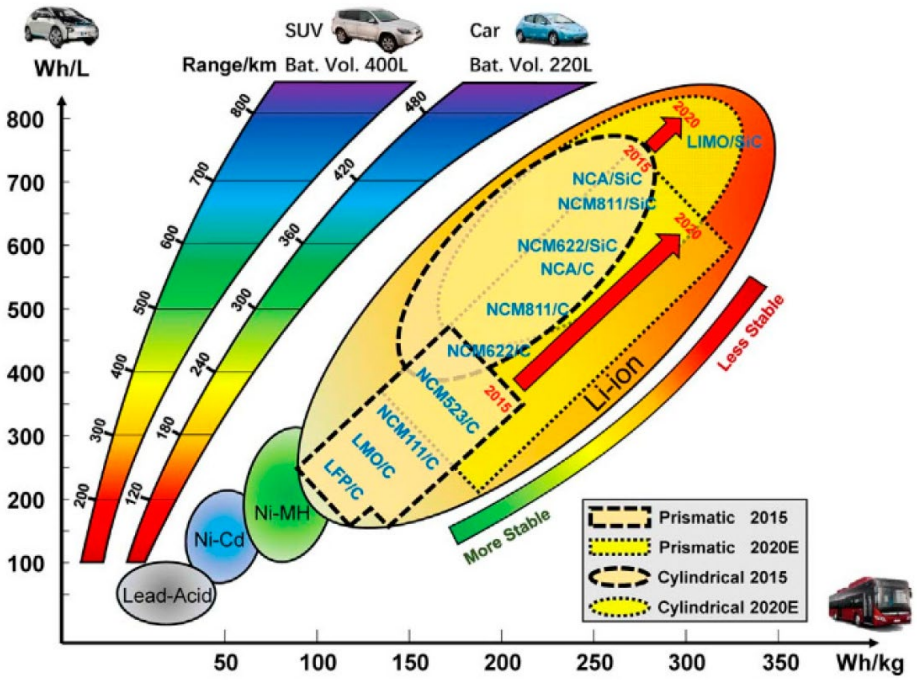
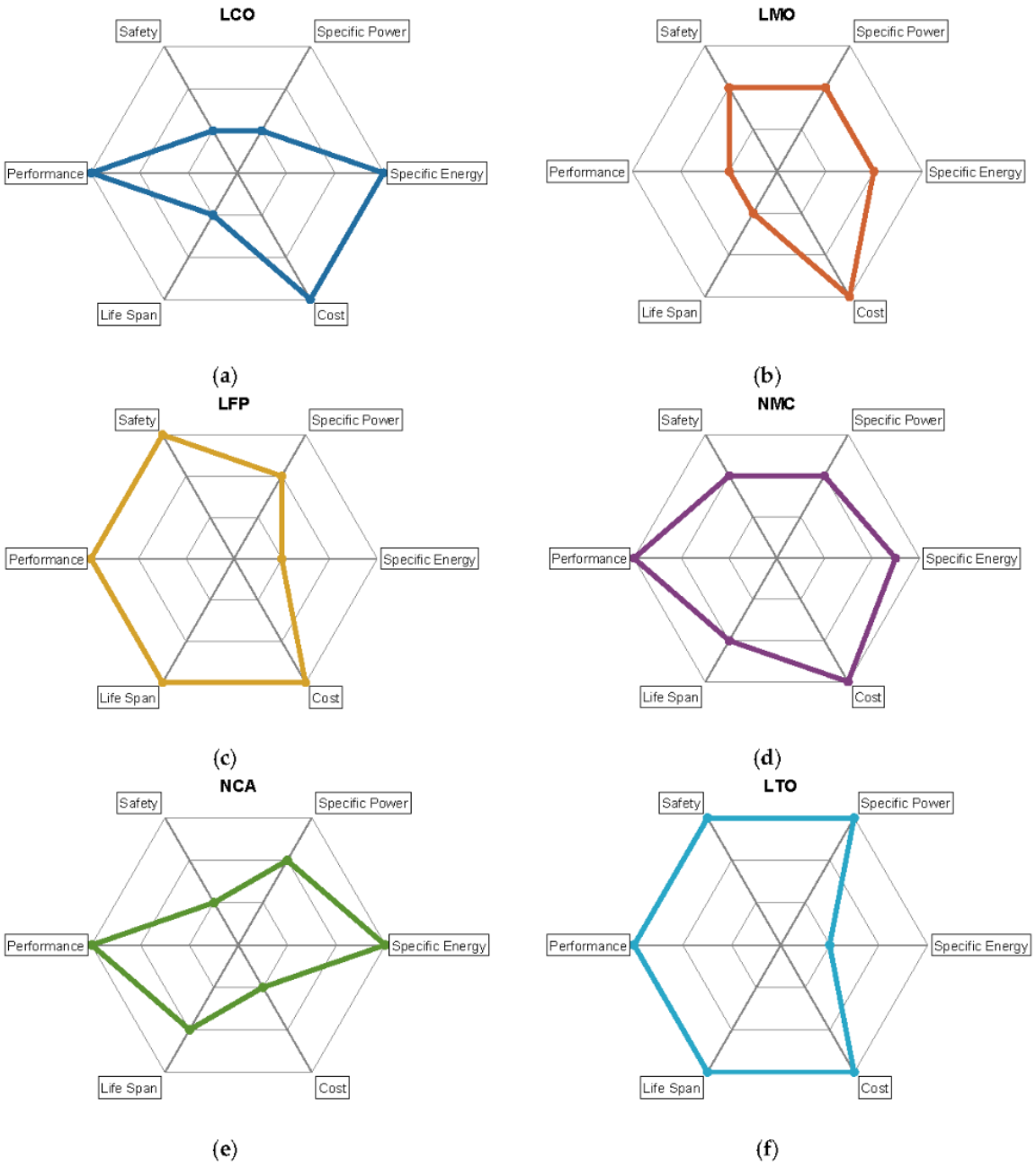


Figure. Li Ion Battery roadmap, (G. Saldaña et.al., 2019).
(Courtesy of Gaizka Saldaña)

Gaizka Saldaña, José Ignacio SanMartín, Inmaculada Zamora, Francisco Javier Asensio, and Oier Oñederra, (2019). Review, Analysis of the Current Electric Battery Models for Electric Vehicle Simulation. DOI: 10.3390/en12142750

Appendix II – Cell Chemistries Comparison



Lithium-ion (Li-Ion) technology comparison.
(a) LCO; (b) LMO; (c) LFP; (d) NMC; (e) NCA; (f) LTO
(G. Saldaña et.al., 2019). (Courtesy of Gaizka Saldaña, 2021).

Appendix III – Cell Chemistries and Characteristics

Cell chemistries advantages and disadvantages
content reconstructed from Kushnir, D., (2015).

CATHODE MATERIAL				
MATERIAL	VOLTAGE	SPECIFIC CAPACITY (mAh/g)	ADVANTAGES	DISADVANTAGES
LCO	3,9	140	Performance, well understood	Safety, uses nickel and cobalt
NMC(333)	3,8	160-170	Better safety and performance than LCO	Cost, nickel and cobalt
LFP	3,4	170	Excellent power, lifetime and safety, abundant materials	Low energy density
LMO	4,1	100-120	Cheap, abundant, high power	Lifetime, low capacity means low energy density
NCA	3,8	180-200	High capacity and voltage, high power	Safety, cost, uses nickel and cobalt

Appendix IV – Attended/Accessed Webinars.

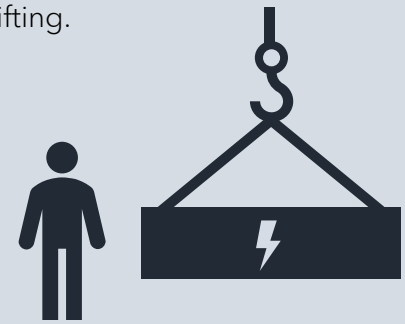
Webinar	Responsible	Date
Why including women is the missing key to innovation, speech by Katrine Marçal	KTH Innovation	8th Mach 2021
(Sustainability Conference) Miljöstrategidagarna 2021. • Sustainable purchase by Kristin Tallbo, sustainability strategist at SKL Kommentus Inköpscentral. • EcoDesign 4.0 by Anna Velander Gisslén at SVID. • The Green Taxonomy by Magnus Astberg, Economic Advisor, The EU Commission in Sverige.	Miljö & Utveckling	9th March 2021.
(Course in materials substitution) "Så tar du reda på om dina kemikalier innehåller farliga kemikalier - Grundkurs I substitution".	RISE	18th March 2021
(Climat crisis) Book release "En strimma av hopp : Klimatkrisen och det postfossila samhället", by the Staffan Laestadius, Professor Emeritus in Industrial Development at KTH.	Klimatpodden and Biblioteken i Göteborg	23th of March 2021
(Sustainability) "Öppen föreläsning om att ställa om" by Nina Wormbs, Professor in Technical History.	KTH Innovation	24th of March 2021
Stena Recycling webinar - From waste to new circular Products	Stena Recycling	15th April 2021
"The lithium-ion battery recycling market" talk by Hans Eric Melin Talk at NAATBatt International 2021.	NAATBatt International	9th February 2021 Accessed April 2021
"Report 2021" Åsa Domeij, Chairman of the Delegation for Circular Economy, presents the Delegation's report to Per Bolund, Minister of the Environment and Climate of Sweden.	Delegation for Circular Economy	14th of April 2021 Accessed April 2021
"Critics against circular economy – What can we learn from it?" talk by Hervé Corvellec, Professor in Business Economics at Lund University.	Hållbar Utveckling Skåne and Cradelnet SYD	20th of October 2020 Accessed April 2021

Appendix V – Observation LIBs Recycling (Volkswagen Facility)

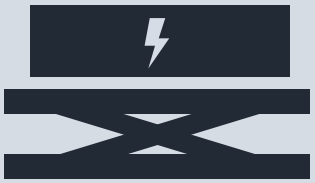
1. Battery transport and handling with a forklift truck.

2. Unpacking.

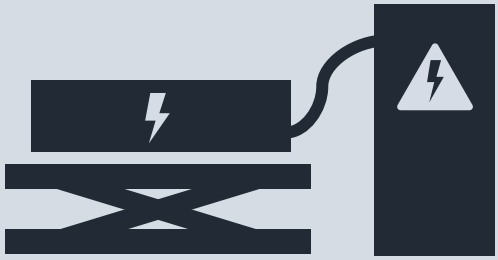
3. Lifting.



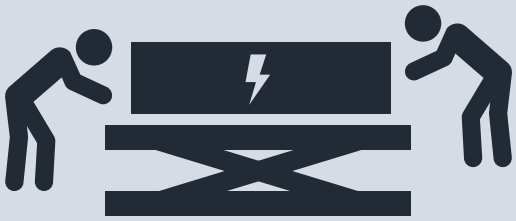
4. Placed on a table, providing better ergonomy.



5. Discharge.

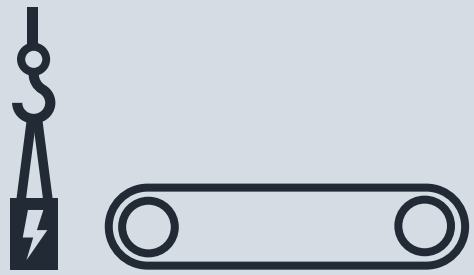


6. Manual dismantling.



7. Disassembly into modules. The operator uses a skewer as a lever to initially lift the modules partially from the system.

8. Lifting modules onto conveyor belts.



9. Two peoples strength seems to bee required to lift one module when moving it from one conveyor belt to the other. It looks heavy.

10. Transportation to the shredder.

11. A mechanical shredder processes the battery into granulate.

12. Separation into different fractions. The sieve separates the valuable cell materials (lithium, nickel, manganese, cobalt) from the raw material.

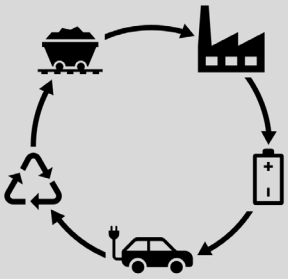
13. Magnetic separator, the magnetic separator collects all of the magnetic raw material from the granulate.

14. Different fractions are separated into separate containers. Plastics/synthetic substances, aluminum, and copper, black mass.

Source:
(YOUCAR, 2021)
https://www.youtube.com/watch?v=Qi8Y2lF7Luw

Appendix VI – Design Guidelines Scoring

HOW RELEVANT ARE THE DESIGN FACTORS?										
No.	Design Factor	Description	1=least, 5=most, N/A=Not Applicable							
			1	2	3	4	5	N/A	Optional Comment:	
1.0	GENERAL									
1.1	Know Why & How	•Knowledge of incentives (Why), and strategies (How), in order to make DfR happen. •Leaders to substantiate work. •Purchase/R&D as setting the level.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.	
1.2	Prior modular design of modules	•Enable selectively switching out modules in systems, to be sent for recycling at EoL. •Replacing the weakest module improves the capacity in the remaining system. •Can facilitate transport, since separated modules don't require expensive custom size containers.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.	
2.0	MARKING									
2.1	Avoid physical labels	•Challenging to wash away physical labels in the recycling process, depending on adhesive.	1 ☐	2 ☐	3 ☒	4 ☐	5 ☐	N/A ☐	Click or tap here to enter text.	
2.2	Use recyclable marking	•Readable for humans and machines. •Aims to keep down the number of materials. •E.g: include in design as insert in mold-, punch- or stamp- tool; Laser; Mechanical stamp.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.	

3.0	MARKING CONTENT									
3.1	Cell chemistry	Clearly marked physically on modules and systems. •To avoid cell chemistries getting mixed since it can seriously damage the material recovery of the black mass compounds.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☒	N/A ☐	Click or tap here to enter text.
3.2	Value chain as circular loop	•Visualized with symbols on each module •Create awareness to whoever cross the product during its life, important in later stages. •Aims to create impetus to trigger action to close the loop. •Concept example: 	1 ☐	2 ☐	3 ☒	4 ☐	5 ☐	N/A ☐	Click or tap here to enter text.
3.3	Mark each different material	•State type to enable pre-sorting into different recycling streams. Make readable for humans and machines. •Pre-sort promote more efficient recycling •Not used much today but enable pre-sorting and can ease it= future-proof.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.

4.0	QR CODE	•Refer to a link=easy to adjust info, and link further. Example of marking combination: 	1 ☐	2 ☐	3 ☐	4 ☐	5 ☒	N/A ☐	Click or tap here to enter text.
4.1	Cell type (QR content)	(Cylindric/prismatic/pouch) •Different types can act different in the recycling process.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
4.2	Historic data (QR content)	•Serial number based for traceability.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
4.3	Materials List (QR content)	•Facilitate selection of recycling strategy. •Hints material value and motivates disassembly.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
4.4	Recycling info (QR content)	•Tells how to act + related safety info. •Reduce barriers for recycling.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
5.0	SAFE HANDLING								
5.1	Mark high voltage joints	•Use colorful orange cables, equivalent to used in EV applications.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
5.2	60 V separation steps	•Allow easy and safe separation of system into lower voltage sections.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
5.3	No protruding terminals	•On modules to avoid short circuit and electric chock.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.

5.4	Consider Poka-yoke solutions	• E.g. a system must be separated into lower voltage sections to make modules movable or to reach other connection points. To ensure safety.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
5.5	Enable easy lifting	•Provide handles and/or attachment points. •Place to avoid short circuit/electric chock. •Consider ergonomics, designing modules to be lifted manually. Prior 15 kg max. •Place for easy access for both human and machine.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
5.6	Don't exceed stated max temp of cells.	•Can differ, but generally Max=60 °C. •Keep batteries below this tempt to avoid changing characteristics of the active materials.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
6.0	DISCHARGE								
6.1	From system level (Prio 1)	•Safer as the internal BMS and the internal sensors are used.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
6.2	From module level (Prio 2)	•Make terminals easy to access and connect. •Design to avoid corrosion and dirt. •Provide discharge info.	☐	☐	☐	☒	☐	☐	Click or tap here to enter text.
6.3	Cell level (Prio 3)	•Make poles accessible. •Provide discharge info.	1 ☐	2 ☐	3 ☒	4 ☐	5 ☐	N/A ☐	Click or tap here to enter text.

6.4	Disclaimer of cell level	•Cell bonds can break which hinders the discharge required for recycling. This can result in a severe risk of danger. •Broken bonds can be difficult to detect. •Caution must be taken. •Consider discharge in line with following 6.5 to ensure safety.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
6.5	As last resort (Prio 4)	•E.g. if or hazardous cases, broken welds/ bond wires of cells. •Enable handles/ attachments to be used to safely immerse system/module in liquid. e.g. saline (it do not affect black mass recovery via hydromet). •Select salinity to accomplish conductivity to discharge by ≤0,05C, to ensure safety. •Make sure liquid reaches batteries. -One or two uncharged cells might be ok. But the topic needs further investigation.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
8.0	DISS-ASSEMBLY								
8.1	Separation of system from application	•Already sectioning into safer voltages.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
8.2	Separation into single modules	•Recycling and shredders can handle limited sizes. Preferably below 1 meter. A rectangular shape with thickness is preferred over a cubic shape.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.

8.3	Separation into main fractions	•Enable pre-separation of the module into PCBs; electronics; metals plastics and batteries, to be sorted into each destined recycling stream. •separated before shredding avoid contamination between fractions to improve material recovery.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
8.4	Prior separation of metals, electronics, PCBs	If separation is restricted, prior to separate: •Metals: mixed in the black mass, e.g. iron and aluminium, can hinder recovery in hydromet. •PCB/electronics: contain tin which is bad for hydromet.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☒	N/A ☐	Click or tap here to enter text.
8.5	Disclaimer of disassembly to cell level	•Broken cell bonds hinder required discharge=difficult to detect=severe risk of danger. •Disassembly into separate cells can result in cells short circuiting each other. •The cell holder might be a more suitable level, if made by plastic. Plastic do not hinder black mass recovery but can contrary be contaminated by the battery chemicals. •Consider discharge in line with design factor 6.5 to ensure safety.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
8.6	If materials cannot be separated	•Ensure different materials will be separated through shredding.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.

8.7	Use minimum number of fasteners per module	•Approx. 4-5 operations might be acceptable. •Few steps=incentives to disassemble (time/cost/revenue)	1 ☐	2 ☐	3 ☒	4 ☐	5 ☐	N/A ☐	Click or tap here to enter text.
8.8	Use same type and size of fasteners	•Limit tools required	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
8.9	Prior snap locks & screws	•Avoid permanent joints	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
8.10	Design for automation	•Make joints reachable and discountable from the same axis as much as possible. •Work with high contrast to ease detection of joints, gripping area, etc.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
9.0	MATERIAL SELECTION								
9.1	Same as in the battery cell	•Chose already present materials to keep down the total number of materials.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
9.2	Green PCBs	•Use the general green color for PCBs, since many recycling facilitates detects and sorts the by its typical green color.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.

10.0	ADHESIVES								
10.1	Avoid adhesives, thermosets and potting	•Mechanically hinders recycling. •Common compound can interfere and hinder black mass recovery, such as thermal pre-treatment hydrofluoric acid, which is very corrosive.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.
11.0	OTHER SOLUTIONS								
11.1	Reuse or recycle? *Further explained in appendix 1.	•This is a gray zone difficult to assess. •An objective evaluation system, stating best practice per case, should be developed. •As an internal or centralized solution. Preferably accessed via QR code.	1 ☐	2 ☐	3 ☐	4 ☒	5 ☐	N/A ☐	Click or tap here to enter text.

Appendix VII – Scoring Table – Answers

Answ.	Factor	No.	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	TOT	AVERAGE
10	know why	1.1	5	4	5	4	5	5	5	2	3	4	42	4,20
9	modular design	1.2	2	4	N/A	3	5	4	3	2	5	4	32	3,56
9	avoid phys. labels	2.1	3	3	3	3	5	2	2	2	5		28	3,11
9	recylable marking	2.2	4	4	4	4	5	3	3	4	4		35	3,89
8	cell chemistry	3.1	5	4	N/A	5	5	5	5	5	5		39	4,88
10	circle	3.2	3	2	4	5	3	3	1	4	3	2	30	3,00
9	mark materials	3.3	4	4	4	4	1	4	4	5	4		34	3,78
9	QR	4.0	5	5	5	5	5	4	4	4	5		42	4,67
9	Cell type	4.1	3	4	5	4	5	4	4	4	5		38	4,22
9	Historic	4.2	3	5	5	5	5	3	4	4	5		39	4,33
9	Material list	4.3	4	5	5	4	5	3	4	3	5		38	4,22
8	Recycling info	4.4	5	4	5	5	N/A	3	5	4	4		35	4,38
10	mark high volt	5.1	5	4	5	5	3	4	4	5	4	4	43	4,30
10	60 v sep	5.2	5	4	5	3	3	5	3	5	4	3	40	4,00
10	no protrud	5.3	5	4	4	3	3	2	4	5	4	4	38	3,80
10	Poke-yoke	5.4	5	4	5	5	5	4	4	4	3	4	43	4,30
10	lifting	5.5	3	4	4	5	2	5	3	4	4	3	37	3,70
9	max temp	5.6	4	5	5	4	5	3	4	5	5		40	4,44
9	system level	6.1	3	4	5	5		5	3	5	4	3	37	4,11
9	module level	6.2	5	4	4	4		4	5	5	5	4	40	4,44
9	cell level	6.3	2	2	4	5		3	5	3	5	2	31	3,44
8	disclaim	6.4	3	3	4	5		2	4	3	5		29	3,63
6	last	6.5	4	3	5	N/A		4			4	2	22	3,67
9	system	8.1	5	4	5	4	5	4		4	3	2	36	4,00
9	into modules	8.2	5	4	4	4	4	5	N/A	4	5	3	38	4,22
8	into main fractions	8.3	5	4	4	3	5	4	N/A	5	5		35	4,38
6	prior met, el., circ.	8.4	4		4		5	4	N/A	5	5		27	4,50
6	disclaim. cell level	8.5	4	3	5			3	N/A	5	4		24	4,00
8	shredder	8.6	3	3	5	3	5	4	5	N/A	5		33	4,13
9	min fasteners	8.7	2	4	3		5	4	3	3	4	3	31	3,44
10	same type and size	8.8	3	4	3	5	4	3	4	5	5	3	39	3,90
10	snaps and screws	8.9	3	4	3	3	5	2	3	5	5	4	37	3,70
9	design for auto	8.10	3	4	4		5	3	4	3	5	4	35	3,89
8	same as battery	9.1	2	4	5	N/A	5	4	4	4	5		33	4,13
8	pcb green	9.2	5		4	5	5	2	2	5	4		32	4,00
9	avoid adhesive	10.1	4	4	3		5	4	3	5	4	3	35	3,89
6	Reuse or recycle	11.1	2		4		5	4	4		4		23	3,83

Not answered or N/A

Levels of green visualize factors with high score.

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
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