Lund university
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Master Thesis

Mapping the European reverse logistics of electric vehicle batteries

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Abstract

Lithium ion batteries enable the implementation of renewable energy and electric vehicles, both of which are crucial for the transition to a sustainable society. Due to environmental, economic and political reasons, these batteries must be recycled efficiently. Most lithium ion batteries are placed on the market in electric vehicles, which are reaching end-of-life at a exponential pace, prompting the need to rapidly develop an efficient reverse supply chain of electric vehicle batteries. Due to the market speed, the complex ecosystem of actors and regulations and the inherent dangerous properties of lithium ion batteries, this reverse supply chain is still in its infancy and yet to be understood.

The purpose of this thesis was to conglomerate the knowledge in the literature and among the field experts, to map out the current state of the reverse supply chain of electric vehicle batteries and identify gaps of information and understanding. The goal was to illuminate which aspects to consider when strategically deploying a lithium ion battery pretreatment plant in Europe by answer the following research questions:

1. Which aspects influence the European logistics of end-of-life electric vehicle batteries transported for recycling today and how may these change in the near to mid-term future?
2. How do these aspects influence the strategical deployment of lithium ion pretreatment plants in Europe to facilitate efficient entry to recycling streams?

First, this study carries out an in-depth literature research to identify the public knowledge gaps. Secondly, these knowledge gaps were answered through qualitative, semi-structured interviews with 22 market experts from all parts of the return logistics. The research was commissioned by Northvolt and the research was mainly carried out during the development of their pilot pretreatment plant.

By analysing the findings from the interviews and leveraging knowledge from the literature research, a uniquely detailed map of the EV battery return flow was developed. The map includes the actors and stakeholders as well as the key aspects, events and processes and was divided into the natural and the unnatural return flow, which in turn were divided into multiple smaller return flows. The maps may advice a strategical deployment of a recycling pretreatment plant and, finally, the key takeaways were:

- the need for increased traceability
- the need for clearer and better enforced regulations for storage and transportation
- a transparent secondary market could enable better sourcing for remanufacturers and recycling.

Sammanfattning

Litiumjonbatterier möjliggör implementering av förnybar energi och eletriska fordon, vilka båda är avgörande för omställningen till ett hållbart samhälle. På grund av miljömässiga, ekonomiska och politiska skäl måste dessa batterier återvinnas effektivt. De flesta litiumjonbatterier släpps ut på marknaden i elektriska fordon som når sin livslängd i en exponentiell takt, vilket skapar behovet av att snabbt utveckla effektiva returflöden av elbatterier. På grund av den snabba marknadsökningen, det komplexa ekosystemet av aktörer och förordningar och de inneboende farliga egenskaperna hos litiumionbatterier är denna omvända leveranskedja fortfarande i sin linda och föga förstådd.

Syftet med uppsatsen var att sammanställa kunskapen inom elbilsbatteriernas returlogisik från litteraturen och industriexperter och därefter kartlägga det aktuella läget. Elbilsbatterier är tunga och potentiellt farliga, vilket gör transporten väldigt dyr och komplicerad. Det finns fördelar med att utveckla ett nätverk av förbehandlingssanläggningar som bryter ner elbilsbatterierna till hanterbart material. Målet med uppsatsen var därför att belysa vilka aspekter som ska beaktas vid strategiskt uppförande av förbehandlingsanläggningar (pretreatment plants) för litiumjonbatterier i Europa. Avhandlingen syftade till att svara på följande forskningsfrågor:

1. Vilka aspekter påverkar den europeiska logistiken för uttjänta elbilsbatterier för återvinning idag och hur kan dessa förändras i framtiden?
2. Hur påverkar dessa aspekter den strategiska utplaceringen av förbehandlingsanläggningar för litiumjonbatterier i Europa för att underlätta ett effektivt tillgång till returflöden?

Studien genomfördes genom en bred litteraturforskning för att identifiera de publika kunskapsluckorna. De publika kunskapsluckorna fylldes i genom kvalitativa, halvstrukturerade intervjuer med 22 marknadsexperter från alla delar av returlogistiken. Forskningen stöttades av Northvolt och utfördes i samband med utvecklingen av deras pilotanläggning för återvinning av litiumjonbatterier.

Efter analys av intervjuerna och kunskapen från litteraturforskningen utvecklades en unikt detaljerad karta över returflödet för elbilsbatterier. Kartan inkluderar aktörer och intressenter samt nyckelaspekter, händelser och processer. Returlogistiken uppdelad i det naturliga och det onaturliga returflödet, som i sin tur delades in i flera mindre returflöden beroende på den verkliga världshändelsen. Kartan kan ge råd om en strategisk användning av en förbehandlingsanläggning för återvinning. De viktigaste insikterna är behovet av ökad spårbarhet samt tydligare och bättre tillämpade lagar och regler för lagring och transport. En transparent andrahandsmarknad skulle underlätta optimal återanvändning och återvinning genom att göra det möjligt för aktörerna att införskaffa batterierna för just deras processer och applikationer.

Acknowledgement

I would like to thank Northvolt as a whole for their inspirational journey towards manufacturing the world's greenest lithium ion batteries, promising a brighter future. A special thank you to Ingrid Karlsson, my supervisor, and the Revolt team for guiding me through the thesis and providing unique expertise on the topic of lithium ion battery recycling.

Thank you Mats Andersson for tirelessly helping me with weekly meetings and great feedback.

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William Bergh
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Nomenclature

ATF Authorised Treatment Facility

BEVB Battery Electric Vehicle Battery

BMS Battery Management (or Monitoring) System

CoD Certificate of Destruction

DOD Depth of Discharge

ELEV End of Life Electric Vehicle

EOL End Of Life

E1U End of First Use

E2U End of Second Use

EfU End of Final Use = EOL

EV Electric vehicle

ELV End of Life Vehicle

ELIB End of Life Industrial Battery

EVB Electric Vehicle Battery

HEV Hybrid Electric Vehicle

LIB Lithium Ion Battery

PHEV Plug-on Hybrid Electric Vehicle

POM Put On Market

PTP Pretreatment Plant

RUL Remaining Useful Life

SESS Stationary Energy Storage System

SOC State Of Charge

SOH State Of Health

SOS State of Safety

VSM Value Stream Mapping

VUW Vehicle with Unknown Whereabouts

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1 Introduction

In this chapter, the overall topic of the study, its background and problematization is found. Furthermore, the purpose and the research questions are defined and lastly, the scope, limitations and outline are presented.

1.1 Background

Since they were commercialised in 1992, lithium ion batteries (LIBs) have been used in all types of portable electronics. As video cameras and mobile phones, smart phones, computers and tablets grew in number, symbiotically did lithium ion batteries. Since 2010, when the first serial electric vehicles (EVs) were launched, the lithium ion batteries have been enabling the electrification of the mobility and energy sector, leading the transition towards a sustainable society. A booming demand for electric vehicles has pushed the production of lithium ion batteries to grow exponentially. In only 6 years, the batteries placed on market (POM) in electric vehicles outgrew the ones in all portable electronics [1]. The lithium ion battery production is predicted to grow at least fourteen times between 2020 and 2030 [4, 27].

The lifetime of lithium ion batteries varies greatly depending on usage. Large systems such as electric vehicles tend to average 8-10 year [2]. In electric busses with their inherent intensive cycling patterns however, the lifetime can be as short as 4-7 years [28]. Consequently, the amount of lithium ion batteries reaching end of (first) life (EOfL) will follow the POM-curve with a lag of 4-10 years.

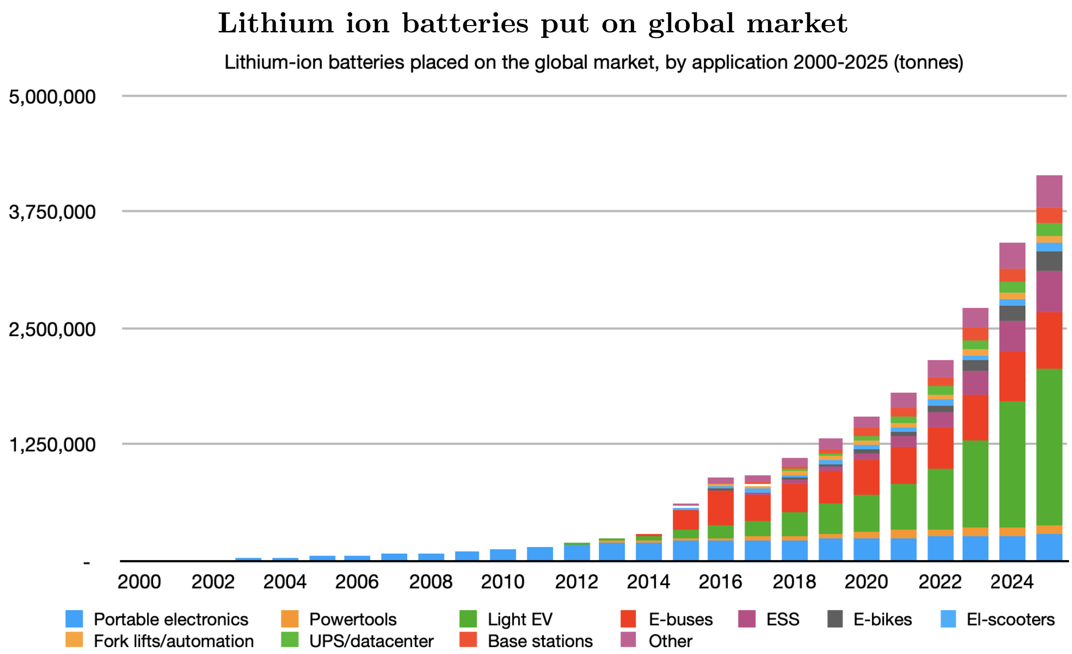

Figure 1: Electric vehicles outgrew consumer electronics in 2016, and will increasingly dominate the applications in which LIBs are placed on market. [1]

When LIBs reach end of first life they can either be reused in a similar application, re-purposed and used in new applications (so called second life) or be recycled [**?**]. However, because of environmental, economic and geopolitical issues, all lithium ion batteries should nevertheless always be recycled at end of life (EOL).

The environmental reason for recycling is based on the emissions lithium ion batteries carry from production. Recycling the batteries dramatically reduce the emissions associated with LIBs [29, 4], as much as up to 70 %[30]. The economic issues are based on the limited supply of virgin material and the weak supply chain with few players [31]. Increased scarcity will increase the costs of mined material while recycled material will become cheaper as volumes increases and process development proceeds. Also, the battery makes up 30-50 % of the electric vehicle cost [2]. This high value material is attractive to feed back into production through a circular economy. The geopolitical issue is based on Europe's low influence on the LIB supply chain. Europe produce around 5 % of the global output of lithium ion batteries [27]. The leading actors throughout the lithium ion battery supply chain are all in South East Asia, dominated by China, due to their experience in producing consumer electronics [32, 33, 30, 34]. In 2015, China's production shares of the cobalt supply chain were; mine 14%, intermediate 33% and refinery 50 % [35]. Looking at entire Asia, in 2016 it amounted to 88% of the LIB production for all end-user application, including 85% of cathodes, 97% of anodes, 84% of separators and 64% of electrolytes [32]. This global imbalance of market power causes European dependency on foreign powers for critical energy infrastructure and electric mobility [34].

To minimise the environmental impact of lithium ion batteries and be economically and politically competitive in the long term, Europe must intercept the return logistics of electric vehicle batteries and recycle them within Europe. However, LIB recycling is not perfectly straight forward.

LIB recycling can generally be split into two parts. Firstly, the pretreatment process that involves discharge, dismantling, crushing and separation, finally producing "black mass". The black mass is a mix of the materials in the anode and cathode and much simpler to transport than electric vehicle batteries. Therefore, a network of pretreatment plants may be a good strategy to make the return flow more efficient. The second step is the recovery of the materials, in which processes refines the black mass into battery grade material [17, 36, 37]. The second step is much more capital intense and requires large feed volumes, and should therefore be kept at a central recycling plant.

The commissioning company has identified the opportunity of owning their supply of recycled material. By deploying a number of pretreatment plants throughout Europe, they aim to become the largest collector and recycler in Europe. Knowing where and when to develop the pretreatment plant system is crucial for competitiveness. A map of the return logistics of electric vehicle batteries is a key enabler for strategical system development.

Lastly, lithium ion batteries are only as good as the mitigated emissions from alternative fuel sources. As soon as a battery is not cycled, it does not replace the use of fossil fuels. Efficient, cost effective and safe return logistics of electric vehicle batteries is crucial for the transition into a sustainable society.

1.2 Problem Statement

The European Parliament Council (2006) Battery Directive 2006/66/EC states that 45% of all waste batteries batteries on a three-year-average should be collected [38]. However, it does not specifically set any collection targets for industrial or electric vehicle batteries [27]. Sweden has set a collection target of 95%. Nevertheless, Sweden collected 9% of all EOL LIBs on a three-year average in 2017. Generously counted, based on the batteries put on the market 6-8 years prior, the collection rate was 16% [2], thus not reaching the directive targets.

The reasons for the low collection rates of lithium ion batteries are publicly unknown. The situation is difficult to assess due to lack of obligations for European member states to collect and report data [27]. Suggestions are that batteries in consumer electronics, which still make up 80% of EOL LIBs, are being hoarded in their applications in homes or company offices, or are disposed of in other ways. Yet, theses reasons seems implausible since insufficient amounts of consumer electronics are hoarded to fill up the discrepancy between EOL LIBs and collection rates. A more convincing hypothesis is that LIBs are being exported to Asia for repurposing (e.g. in portable power banks) [2]. It is a cheaper solution and arguably better than hoarding. Therefore, collection rates are low in Europe, but relatively high globally. Predominately, recycling is done in China and South Korea (see figure 2), where the industry already is well developed. In contrary to Europe where recycling costs are covered with gate fees, Chinese recyclers are profitable enough to pay for cobalt rich batteries [39, 27].

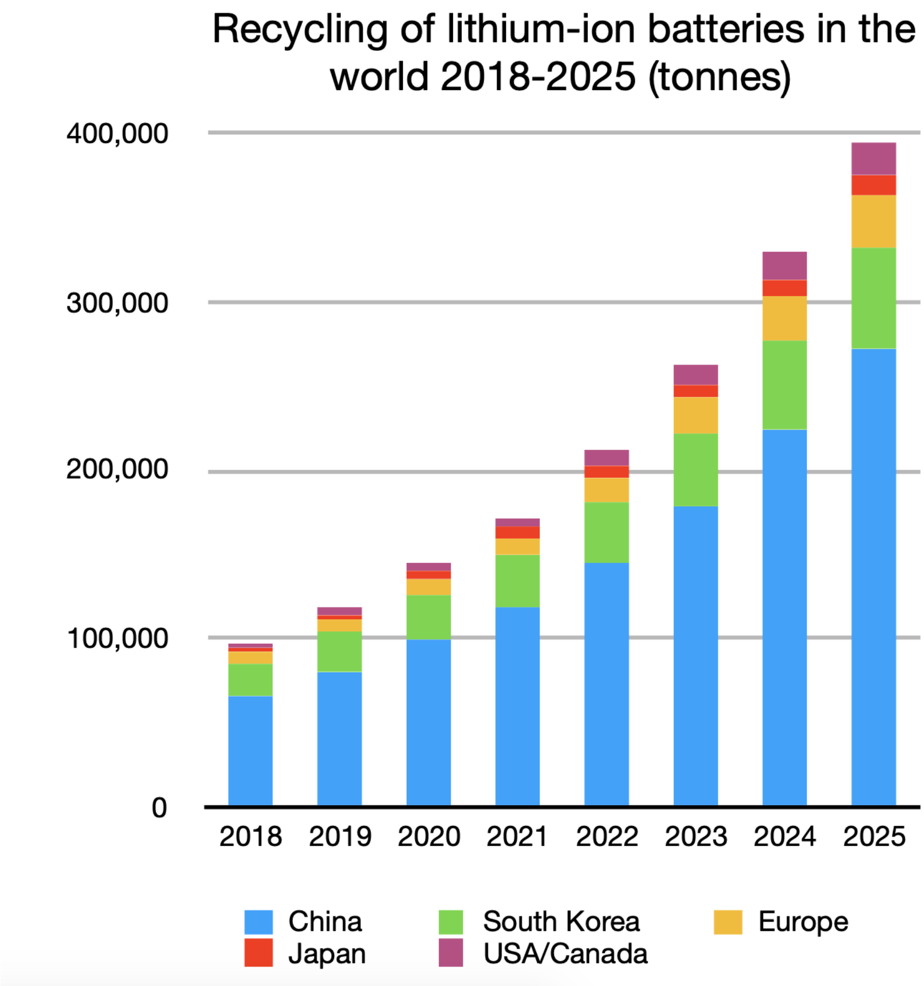

Figure 2: Recycled LIBs 2000-2025 by country. [2]

When LIBs are assembled in electric vehicle batteries (EVBs), rather than in consumer electronics, collection and recycling becomes even more challenging. This challenge will grow with the increasing number of EVBs reaching EOL, especially in Europe where the infrastructure and reverse supply chain is underdeveloped.

Firstly, the reverse supply chain of electric vehicle batteries is underdeveloped due to several reasons. Some of which are:

- Because of a complex supply chain of electric vehicle battery packs, the disposal responsibility is ambiguous. Also, the problem of private people owning large battery systems is novel and the battery directive is mostly developed for portable batteries. Hence, determining who is responsible for the collection schemes is challenging [38, 27].
- EVBs are not standardised. Various different materials, electrochemical characteristics, geometries as well as software protocols has prompted ad-hoc collection and disposal solutions. EVBs has proved difficult to collect, discharge and disassemble at scale [40].
- Most LIBs has historically been re-purposed and recycled in Asia [2]. It has been cheaper for European actors to export end of life batteries to Asia. Europe does not have sufficient recycling capacities yet [2, 1].
- High recycling costs and a dramatic decrease of cost of battery production decrease the incentives to recycle [41].
- The value of an end-of-life battery is based on the materials and the state of health as well as where on the degradation curve the battery is located (remaining useful life, RUL). The further down or further to the degradation knee, the less valuable (see figure 3). A harmonised method of labeling (RUL) is yet to be identified and implemented [42].
- Besides being large and heavy, EVBs are dangerous goods [43]. The risk of fire, release of toxic gases and liquids as well as electric chocks are high and the consequences dire [13]. Storage and transportation is consequently very expensive.

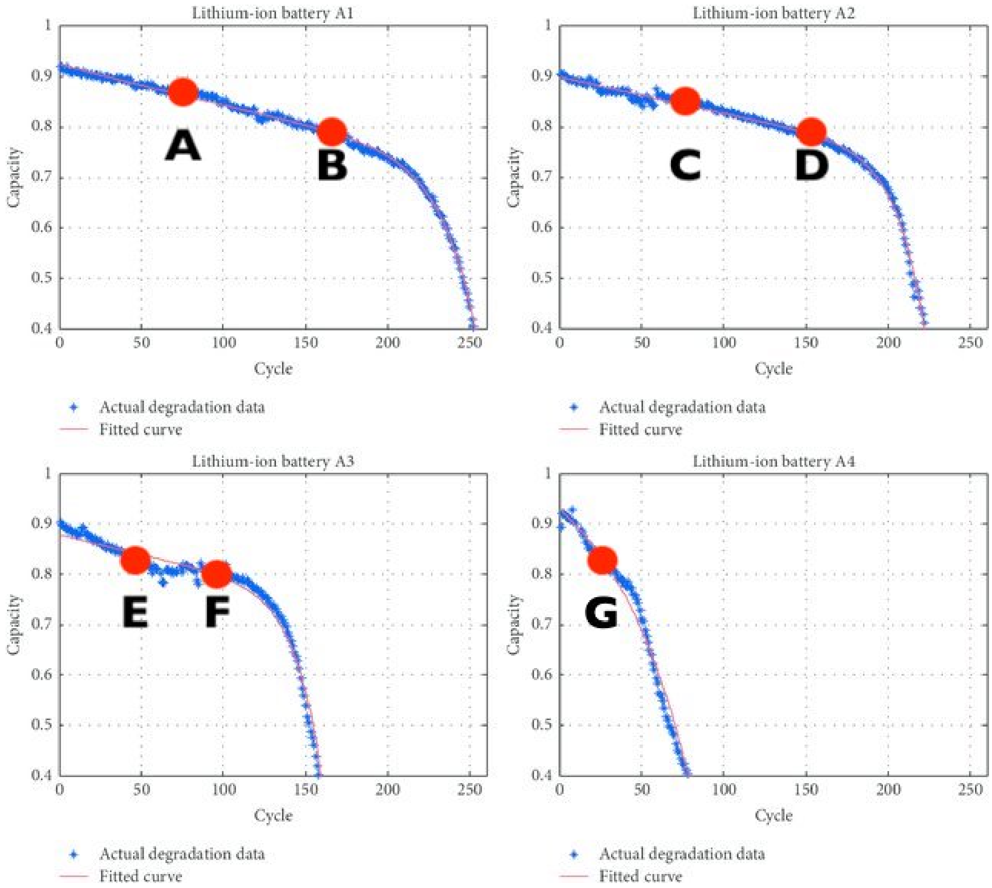

Figure 3: Degradation curve of 4 different lithium ion batteries. The value is higher the more remaining capacity. For example, Batteries at A,C and E are more valuable than at B,D,F and G. Figure adopted from [3], but modified by the author.

Secondly, the problem targeted in this report, is the little to no oversight of the logistical return flow of electric vehicle batteries [5]. There are many projections of how many of each type of battery will return and when. The estimations can be developed quite conclusively based on the historical data of lifespans and number of batteries put on the market. However, there is little gathered data on the real world implications, such as where and how these batteries end up today and how they should end up in the future. In 2019, Melin found no study on the sorting of lithium ion batteries and claim that the research on collection is strongly underdeveloped [2].

Either, the information is unavailable because the young after-market, not gathered because the problem is novel or deliberately confined by experts in the field. The overall consequence of the problem are disorganised re-purposing and recycling schemes. This disorganisation results in poor business development as well as inefficient use of sustainable energy storage that probably is compensated for with fossil fuels. Oversight is required for a cohesive, cooperative and efficient way forward towards optimal use of electric vehicle batteries. Lack of market oversight for EOL EVBs is problematic for several actors, including automotive OEMs, second use remanufacturers, recyclers and producers.

Limited overview of the return logistics, where each must develop their own solution, leaves synergies unidentified. Without oversight, remanufacturers can not source the batteries that fit the technical requirements for their specific applications [44]. This results in prolonged repurposing time. Also, material recovery is more efficient the more specific a recycling process [40]. Recyclers must therefore tune the settings depending on the type of input battery [6]. Lack of ability to categorically source batteries result in increased downtime. Knowledge about where the bulk of the batteries end up, identification and acquisition of end-of-life LIBs is therefore critical for recycling at scale.

Due to hoarding or storage, other disposal methods than recycling (e.g. landfills) or second usage, only 50 % of batteries that reach end of life are available for recycling globally (see figure 4) [1]. Previously, research has provided logistic schematics of the return flow [17, 5]. However, real world implications have largely been left out. In summary, further developing the understanding of the return logistics of electric vehicle batteries is fundamental for closing the loop of electric vehicle batteries.

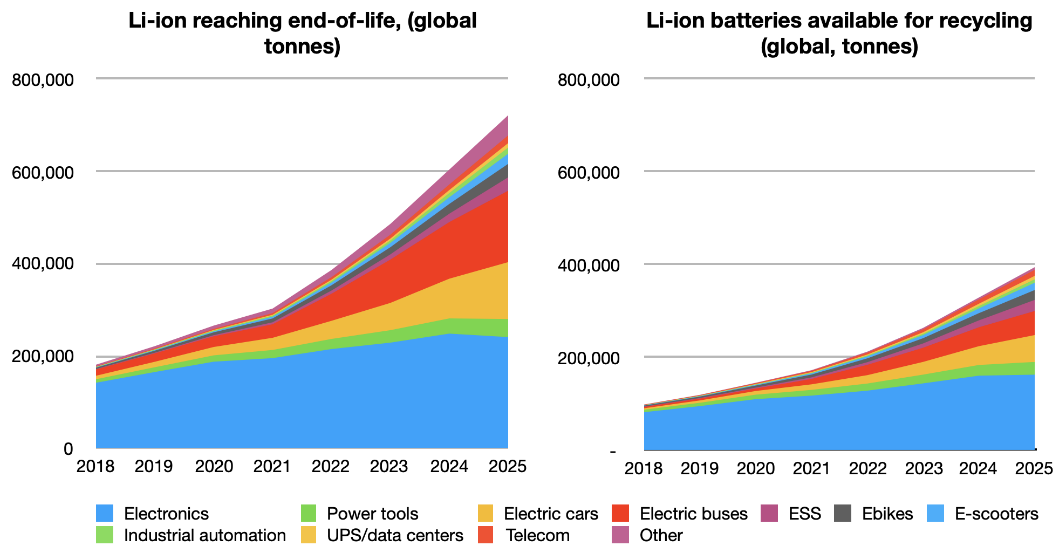

Figure 4: Roughly 50% of the lithium ion batteries that reach end of life are available for recycling. [1]

1.3 Purpose And Research Questions

The return logistics of electric vehicle batteries is futile and based on provisional solutions. The knowledge and expertise is scattered. The purpose of this report is to conglomerate the knowledge among the field experts and the literature to map out the of the current state of the return logistics of electric vehicle batteries and identify gaps of information and understanding. The goal is to illuminate which aspects to consider when strategically deploying a LIB pretreatment plant in Europe.

The research questions:

1. Which aspects influence the European logistics of end-of-life electric vehicle batteries transported for recycling today and how may these change in the near to mid-term future?

2. How do these aspects influence the strategical deployment of lithium ion pretreatment plants in Europe to facilitate efficient entry to recycling streams?

1.4 Scope and Limitations

A strategical placement of a pretreatment plant is based on multiple variables both upstream and downstream. Upstream involves all aspects that relates to the process input, while downstream involves all aspects that relates to what happens with the output of the pretreatment plant (black mass and other waste streams). Due to the logistical challenges of funneling batteries in to a pretreatment processes, the upstream is more influential than the downstream processes where the transportation of black mass from point A to point B is comparatively simple. This thesis will thus foremost be limited to the upstream processes.

The bulk of the lithium ion batteries, and the input to the recycling plants, will eventually be situated in EVs, see figure 5. The regulations and the return flow of lithium ion batteries is quite developed for consumer electronics, however undeveloped for EVBs. Furthermore, the identification and sorting of batteries based on their material composition is simpler for large battery systems compared to single cells. Therefore, the scope of application of this report will be limited to EVBs. There are other return flows that might be interesting to look at, (e.g. lead acid batteries, consumer li-ion batteries and the Chinese RL of EVBs), however none of these provide much guidance when handling large, heavy and high-voltage battery systems. Therefore, other return flows are not prioritised in this thesis.

The EVBs placed on market between 2010 and 2020 are expected to reach end of first life between 2020 and 2030. Today, most EVBs enter the return logistics prematurely (e.g. accident or faulty design), which will not be the case in the future where most EVBs will enter the return flow due to natural EOL (e.g. $SOH < 80\%$). Therefore, because of the delayed critical mass, the investigated time frame stretches from 2020 to 2030, and the first research question could in general be seen as "how does the RL look like today when most vehicles enter prematurely?" and "how should the RL look like in the future when most vehicles enter naturally?".

The data will mostly be gathered within Sweden, and to some degree Norway. This narrow geographic area may limit the generalisability of the findings, making them difficult to apply internationally. Yet, one of the benefits with the limited geography is the fact that Norway and Sweden were early adopters of EVs making the two countries good cases to analyse.

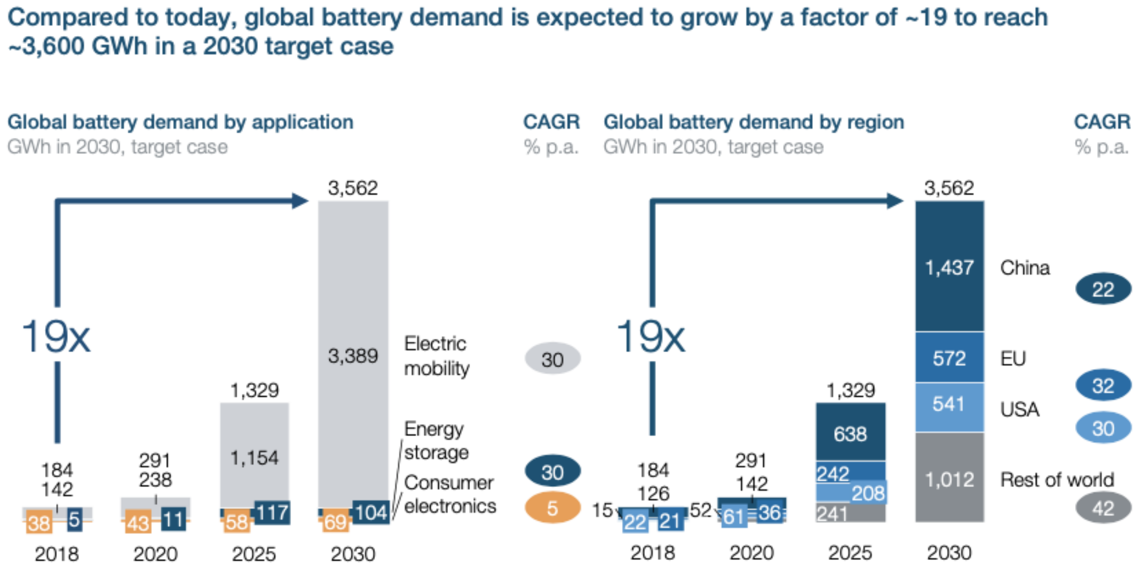

Figure 5: The bulk of the lithium ion batteries will be used in electric vehicles in 2030. [4]

There are strong financial aspects that influence the return flow. However, because this is a qualitative study, where the interviewees are actors in the novel market, little information about their finacial strategies can be expected to be shared. The unit of analysis is thus the physical and geographical collection and sorting of EVBs in time.

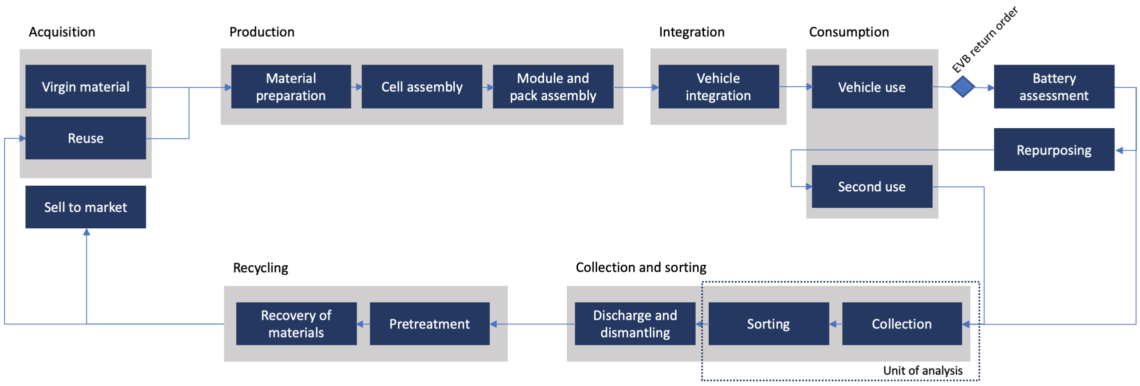

Figure 6: Scope of this report. Figure adopted from [5] and [6]

In general, this thesis purposely takes a wide view of the RL, rather than focusing on one specific part, to illustrate the vastness of the problem and provide insights in where there should be more focused research going forward.

1.5 Outline

To answer the research questions, it was necessary to closely research the current literature. To illuminate the knowledge gaps, questions were posed throughout the Frame of Reference (chapter 3), which later were used for the qualitative interviews with key industry experts. The Frame of Reference thus make up the literature research. The gathered data from the interviews is presented and analysed in Findings and Analysis (chapter 4). In the same chapter, the return flows are illustrated.

In Discussion (chapter 5), the first research question of “Which aspects influence the European logistics of end-of-life electric vehicle batteries transported for recycling today and how may these change in the near to mid-term future?” is answered using the return flows directly. The second research question, “How do these aspects influence the strategical deployment of lithium ion pretreatment plants in Europe to facilitate efficient entry to recycling streams?”, was answered by analysing the return flows further. The Conclusion (chapter 6) states the key outcomes, contribution to research and suggests further research topics. I

It was difficult to find published research papers covering the spectrum from what lithium ion batteries are and how they work, market analysis, regulation analysis and all the practical steps of the return flow. This information is very important to have gathered to further develop the complex return flow, intelligently. Therefore, much effort was spent to exhaust the Frame of Reference.

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2 Method

In this chapter, the methodology is described. It describes how the research was designed and processed, as well as how the data was gathered and analyzed. Finally, it describes how the quality and ethics were related to.

2.1 Research Design

The thesis was developed to map out territory of a newly-identified research problem in an early market. The players in an early market are all trying to find their respective competitive market position. In order to nullify the biases among the market players and to get an real-world aligned understanding of the aspects regarding the placement of a pretreatment, multiple point-of-views were gathered. The research process was developed minding the inherent characteristics of an early international market with new technology, new financial models and many unaligned regulations. Furthermore, there is little published research on the topic, leaving relevant information in the hands of experts and practitioners in the field.

The thesis aims to expand a scientific understanding and general knowledge that answers a number of practical problems and perhaps produce predictions of the future. Embarking on this research journey may lead to insights not specified in the purpose. The research can thus be seen as exploratory basic research [45, 46]. Concerning whether this thesis is inductive or deductive, it may be both. While investigating observations such as "there is no agreed upon standard on the return logistics of electric vehicle batteries" that may result in a theory as to why that is, the thesis is also investigating theories such as "the return flow of electric vehicle batteries is undeveloped" hoping to find a hypothesis to why that is.

Inductive and deductive research can generally be coupled with qualitative and quantitative data, respectively. As the thesis is based on both research methods, both types of data is required. As little data is available in the literature regarding how the return logistics of EVBs look like, but is kept within the field's expertise and confined to the future, this thesis will be based on the qualitative primary data from interviews. The qualitative data gathered from the interviews may be backed up by secondary statistics (e.g. data on number of vehicles on the roads). The research question exists within the realm of "what, when, where and how", but not "why". Therefore, a descriptive approach is suitable [46].

Based on prior arguments regarding the knowledge base being restricted to field experts as the market is infant, the suitable type of sampling suitable in this case is non-probability sampling. This motivate conscious selection of the interviewees. Meanwhile, this study is aiming to map the situation today, advocating the use of cross-sectional sampling where multiple individuals are interviewed.

The research questions was allowed to be updated throughout the course of the project. In turn, therefore, the research design was allowed to be flexible to adapt to both the iterated questions and the new knowledge acquired during the collection process.

2.2 Research Process

In the first stage of research process, the research questions were developed together with the commissioning company. As a strong LIB market player with unique vertical integration from raw material procurement to production and recycling the research questions were developed with an aim of circular economy, honest to where Europe needs to go to meet the environmental targets. As an exploratory research project, the research questions were iterated upon far into the project. Secondly, with the initial research questions in mind, a literature research process using the snowball method begun. This research laid the foundation for the Frame of Reference (chapter 3), in which questions naturally developed. These questions were then used for a second round of literature research, specifically targeting these questions. Where there was a gap in the literature, the question was kept as research sub-question (RSQ). The RSQs were identified with tags. The tags were used to affiliate each question with an interviewee. If an RSQ did not have a corresponding expert, one was searched for online and added to the list of interviewees. In the third stage, data was gathered from interviews with selected experts and practitioners in the field as well as a study visit at a car dismantler. The fourth step was to analyse the gathered data and apply insights at a study visit at a pretreatment pilot plant to check for real-world validity. Concluding, the findings from the case study was discussed and the final version of the research questions answered. See figure 7 for clarification.

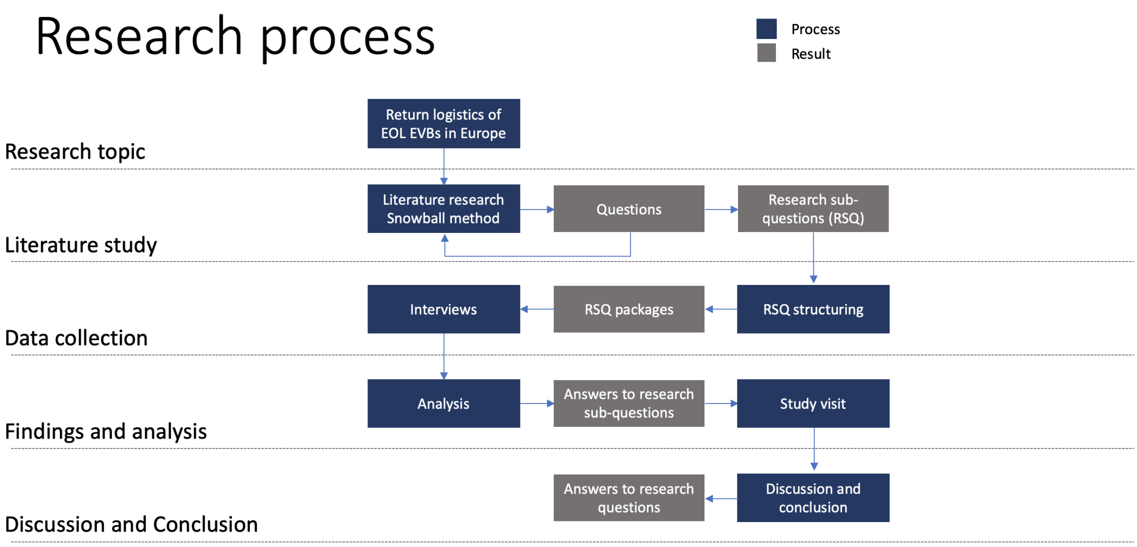

Figure 7: The research process. Own illustration.

RSQ: this is how the sub research questions (SRQs) throughout the frame of reference (chapter 3) will look like.

2.3 Data Gathering

The data was gathered from literature study, interviews and from an on-site visit at the car dismantler being the number one expert on electric vehicle batteries in Sweden.

Literature study

The literature research was initialized with Karlsson and Lindström's master thesis on "lithium ion battery recycling" [17], Hans Eric Melin's reports on "the lithium-ion battery end-of-life market" [1] and on the "state-of-the-art in reuse and recycling of lithium-ion batteries" [2], as well as Ziemba and Prevolnik's master thesis on "the reverse logistics of electric vehicle batteries" [5]. For each interesting section, valuable for this project, the reference was studied and the same procedure repeated creating a sort of "snowballing effect". This method was used to further develop the background and frame of reference. When there was a gap in the snowball-literature, ResearchGate, ScienceDirect and other accessible databases provided peer-reviewed literature. The literature research (constituting the frame of reference, chapter 3) was mostly done prior to the interviews, but was continuously developed as new literature was found throughout the project period.

Interviews

The RSQs resulting from critical analysis of the existing literature were tagged based on area and return logistic event (see figure 8). Area tag meaning the type of expertise that was to answer the RSQ and event tag meaning which part of the return flow the expertise was applied in. The interviews were semi-structured with people from different parts of the EVB return flow.

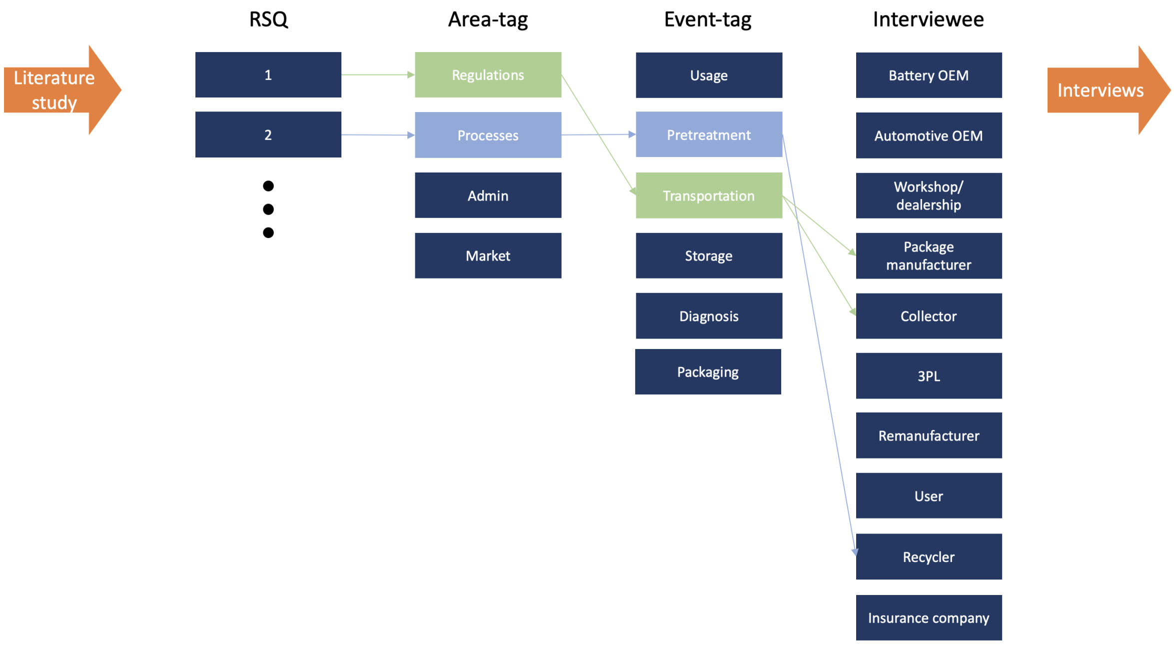

Figure 8: The RSQs were tagged based on area and event. These tags were then used to easily couple the right questions with each interviewee. Own illustration.

Identifier	Actor	Position	Primary theme	Secondary theme	Primary area	Secondary area
A	Industry organisation	Expert	Process		Usage	
B	Industry organisation	CEO	Process	Market	Storage	
C	Insurance company	Expert	Business	Regulation	Collection	
D	Car dismantler	CEO	Process	Business	Storage	
E	Battery OEM	Public Affairs Manager	Regulation		Transportation	Storage
F	Collector	CEO	Process	Business	Collection	
G	Collector	Vice CEO	Business	Market	Collection	
H	Car dismantler	CEO	Process	Business	Collection	Process
I	Automotive OEM	Head of external research	Market	Business	Collection	
J	Recycler	Recycling project manager	Process	Market	Pretreatment	Disassemble
K	Battery OEM	Consultant	Business	Market	Collection	
L	Market analyst	Project Manager	Process	Market	Entire Return flow	
M	Industry researcher	Researcher	Business		Collection	
N	Industry researcher	Consultant	Process	Market	Collection	
O	Car dismantler	CEO	Market	Process	Collection	
P	Packaging company	Global Project Manager	Regulation		Packaging	
Q	Assessment company	Project Manager	Process		Diagnosis	
R	Battery OEM	Expert	Process		Transportation	
S	Insurance company	Expert	Business		Collection	
T	Car dismantler	CEO	Business	Market	Entire Return flow	
U	Car dismantler	CEO	Business		Entire Return flow	
V	Car dismantler	CEO	Process	Business	Collection	Storage
W	Market analyst	CEO	Market		Collection	

Table 1: List of interviewees

Study visit

At the same time as this research was carried out, the commissioning company was developing their pretreatment pilot plant. Analysing the development showed the real-world applicability of the findings of the thesis. The pilot plant was not finished in time for a visit during the project, but was used as a benchmark in the very end to compliment the findings.

2.4 Data Analysis

Thematic analysis is usually perceived to be a good method to analyze qualitative data from interview transcripts, and Ziemba *et. al* showed that it is an effective method for this type of thesis [5]. It is usually made up by the following five steps (excluding writing a report) [47]:

1. Familiarisation with the data

   Transcribing interview if necessary and carefully reading the data. In this stage it is useful to comment initial ideas.

2. Coding

   In a systematic fashion coding the initial ideas in such a way that patterns may be discovered.

3. Generating initial themes

   The codes are collated into themes. Creating blocks of data with similar themes ameliorate the finding of patterns.

4. Reviewing themes

   Check themes against data to see if they make sense.

5. Defining and naming themes

   If a theme makes sense, it can be named. Naming makes further analysis easier to comment on

Traditionally, the thematic analysis is conducted in the data analysis section. However, in this thesis the thematisation was done prior to the data collection, when tagging the RSQs with themes and areas. In this way the questions that emerged from the literature research could be coupled with the suitable expert in the field. After the interviews, the reported data was thus already collated into codes and themes. The literature research and the pre-data collection phase was extensive, but allowed for a more straight forward analysis.

Multiple experts had interdisciplinary knowledge. In these cases, the thematic analysis was repeated. The transcripts were analysed to find different codes, which could be collated into the same themes as the RSQ were collated into.

After the coding and data gathering, value stream mapping (VSM) was used, a method developed by the American researchers Mike Rother and John Shook and after studying Toyota's "material and information flow maps" in the 1990s [48]. VSM is a great tool to map out processes and material flows and to illustrate these in order to improve lean production. The method, as Rother and Shook defines it, is simple: "Follow a product's production path from customer to supplier, and carefully draw a visual representation of every process in the material and information flow. Then ask a set of key questions and draw a "future state" map of how value should flow". In this thesis, those key questions are represented by the RSQ's mentioned in chapter 7.

According to the VSM theory, there is a close relation between current state and future state drawings. A current state is worthless if there is no future state and vice versa. From these two drawings the final step of VSM is to design an implementation plan for the future state. The analysis will focus on developing a desired future state and an implementation strategy based on the gathered data from industry experts.

2.5 Research Quality

The quality (or credibility) is paramount when conducting qualitative research since the data is anecdotal and thus not repeatable in the same way as for quantitative research. Important to understand is that quality research can not guarantee truth, but can minimise the risk of getting the wrong answers [49]. Saunders *et. al* (2009) explains that "Scientific methodology has to be seen for what it truly is- a way of preventing me from deceiving myself in regard to my creatively formed subjective hunches, which have developed out of the relationship between me and my material." [50]. This quote has been taken very much into account. The commissioning company, as for myself, have previous knowledge and "hunches" in the field, all of which must be discounted for when going through the data.

When quality is concerned, two emphases on research design must be paid attention to, namely reliability and validity [49].

Reliability

Reliability refers to the consistency of the findings. Three questions can be posed [49]:

1. Will the measures yield the same results on other occasions?
2. Will similar observation be reached by other observers?
3. Is there transparency in how sense was made from the raw data?

Answering question one, the interviews will probably not yield the same results in the future. This because of the rapid pace of development of the return logistics of electric vehicle batteries. Nevertheless, the aim for this thesis is to map today's situation, and looking into the future. Simply said, the thesis is not supposed to yield consistent results.

Question two is more applicable to this thesis. The literature research was initiated by reading research papers recommended by the commissioning company (referred to in section 2.3), which also were found as top hits when searching for applicable key words in scientific search engines. Because of the snowballing method, however, after the initial literature little "logic" is followed. Snowballing makes the reasoning behind the read literature hard to follow, yet, it allows deeper insights specifically where needed. Regarding the interviews, they were all transcribed (if agreed upon by the interviewee) and anonymised. In this way, if scrutinized, the raw data is available. Saunders (2006) states four threats to the reliability; participant error, participant bias, observer error and observer bias.

The participant error is due to the participant making an error, thus providing answers that would have been other, had the interview taken place some time else. To deal with this threat, the questions were posed before the interview so the participant could prepare.

The participant bias may be due to the participant not feeling free to express their true feelings or honest knowledge. This can be due to their feeling unsure of what they are allowed to say or that they do not want to tell the entire truth. Since all participants in this study are part of companies that are trying to find their place in a new market, this problem is pervading. To deal with threat, all parties of the return flow were interviewed, hoping that different biases were cancelled.

Observer error may be caused by the observer not asking the questions exactly as they were prepared making repetition of the data gathering difficult. The interviews were discussions around open-ended questions, rendering this threat significant. However, the open-ended questions allowed for new questions and insights to manifest themselves, making the method worth the risk. New questions that arose from interview x, were repeated in interview y, if they concerned the same themes.

Observer bias is simply due to the fact that different observers can interpret the same information differently. To eliminate this risk the takeaways from the interview were shared with the interviewees, allowing them to correct any mistakes.

Validity

Validity is important to question in order to conclude whether the data is really concerning the intended problem. Because the thematisation was done before the data-gathering, each question was answered or commented on by participants confident in their field of expertise. There are multiple threats to validity; history, testing, instrumentation, mortality, maturation and ambiguity about casual direction [49]. This thesis must mainly deal with historic and mortality risks.

History-risks concern the point in time the interview was conducted. If there has been a critical new event in the return flow, good or bad, may reflect on too positive or negative predictions. Asking whether such an event had occurred recently was asked in the beginning of each interview.

Mortality-risks concern the drop-out of participants. If follow-up questions and corrections can not be made, the data may not be accurate. To deal with this, each interviewee was asked whether he or she agreed to return corrections or comments on the takeaways from the interview in due time.

Generalisability

This thesis aims to develop a general map of the EVB return flow. Yet, it is important to bear in mind that the market is young and will develop immensely in the coming years.

The research was conducted in Sweden, mostly targeting national experts. Because Sweden and Norway (in which experts also were interviewed) were among the earliest countries with adopting electric vehicles, the return flow will begin in this region. The methods and procedures developed there have a high probability to set example for international return flows. Nevertheless, the conclusions should be followed up regularly in the coming years.

Ethics

As new research questions are asked, new ethical problems arise [51]. Research ethics are thus not static. Researchers are held to high ethical standards as research so prominent in today's society. Committing and following the ethical guidelines is crucial for the trust, which good research depends on. This thesis has followed Good Research Practice as recommended by the Swedish Research Council [51], in which the following general rules are stated:

1. You shall tell the truth about your research.
2. You shall consciously review and report the basic premises of your studies.
3. You shall openly account for your methods and results.
4. You shall openly account for your commercial interests and other associations.
5. You shall not make unauthorised use of the research results of others.
6. You shall keep your research organised, for example through documentation and filing.

7. You shall strive to conduct your research without doing harm to people, animals or the environment.
8. You shall be fair in your judgement of others' research.

In this thesis all interviewees had their identities remained enclosed. Prior to each interview, the candidate was informed about the purpose and the topic of the interview. For transparency, I presented myself as a mechanical engineering student at Lund University conducting the research in collaboration with a Swedish battery company. The interviews were foremost conducted online using video communication platforms, but phone calls and in person meetings were used, too. Before all video interviews, the candidates were asked if it was allowed to be recorded.

3 Frame Of Reference

In this chapter, the theoretical background of the thesis is presented. By researching relevant existing literature, a very wide spectrum regarding lithium ion batteries, electric vehicles and their return flow is covered. Research Sub Questions (RSQ) are included where there is a gap in the studied literature.

3.1 Lithium ion batteries and electric vehicles

Lithium is the third lightest element, has the lowest reduction potential and has one of the smallest ionic radii [52]. These characteristics are perfect for batteries and lithium's continued roll in traction batteries is given in the foreseeable future. Following is a walk-through of the building blocks of an electric vehicle battery.

Cell

A lithium ion battery is made up of an anode, cathode and a separator submerged in an electrolyte, all of which are encapsulated in a metal case. There are three major cell geometries; cylindrical, prismatic and pouch, see figure 9.

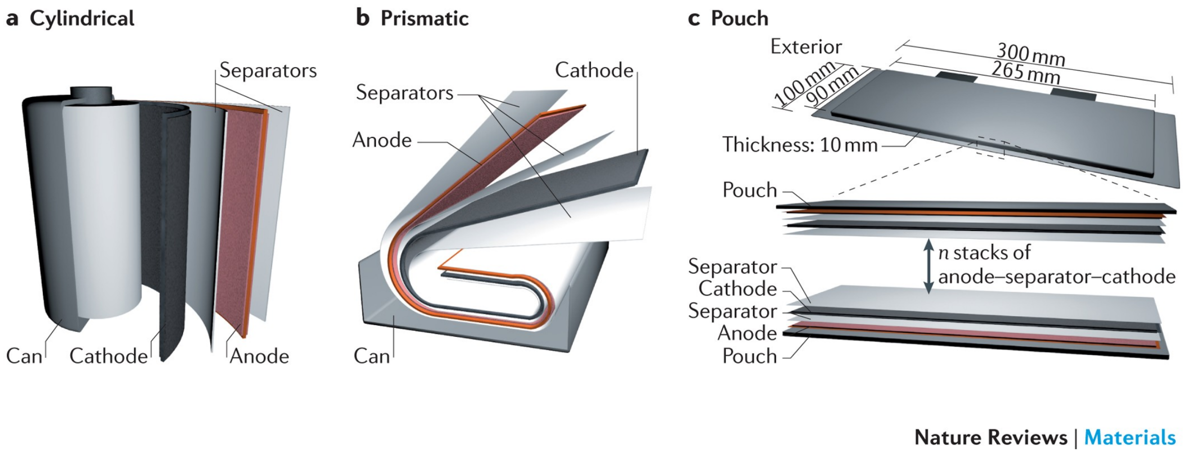

Figure 9: Illustration of the typical lithium ion battery structures; cylindrical, prismatic and pouch cells [7].

The anode is almost unanimously made of up graphite coated on a current collector of copper. Currently however, research is focused on adding other elements for increased performance, such as titanium and silicon [53].

The separator is made of a semi-permeable plastic (often polyethylene or polypropylene) allowing only lithium ions to pass through [30].

The electrolyte is a lithium salt (often $LiPF_6$) in an organic solvent. The salt is generally dissolved in a combination of the organic solutions ethylene carbonate (EC) and dimethyl carbonate (DMC) [39].

The cathode is what chemically distinguish different types of cells, and determines the name of the type of cell. Cathode chemistries and their outlook is presented in chapter 3.2.

Module and Pack

A module is made up of several cells connected in series (to build up power) or in parallel (to build up capacity). Figure 10 illustrates how the cells are placed in modules in a Tesla model S, BMW i3 and Nissan Leaf, respectively. Just like a module is built up by cells, a pack is made up of several modules connected in either series or in parallel. Figure 10 illustrates how the modules are placed in a pack. On a pack level a battery management system (BMS) balances the current output throughout the pack, either actively (by re-routing the current evenly in the pack) or passively (by current peak shaving), monitors the temperature and measures SOC and SOH. The cooling is also done on pack level. The battery pack is usually a high voltage system [8].

The mass of EVBs differ depending on capacity and power requirements of the vehicle. With the introduction of BEVs, the size and weight has increased significantly compared with hybrid electric vehicles (HEV) and plugin hybrid electric vehicles (PHEV).

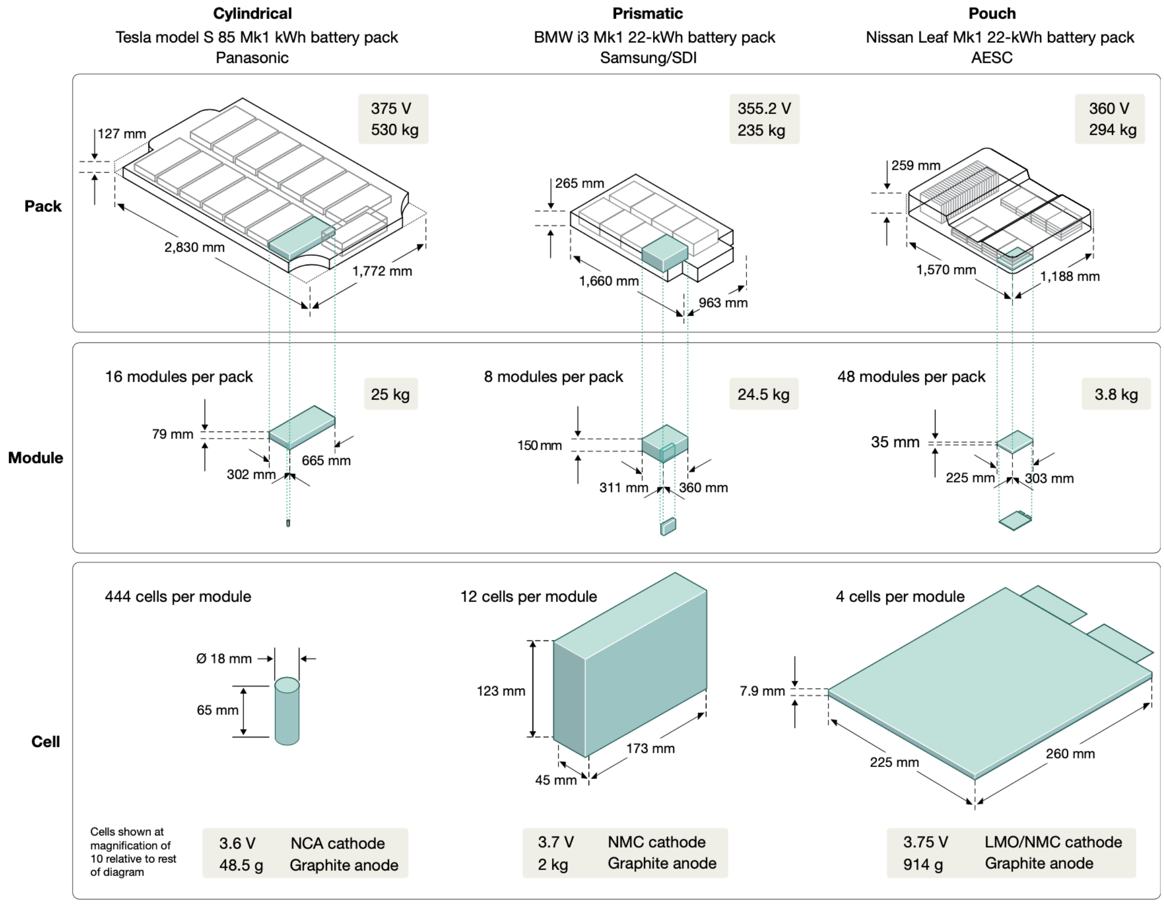

Figure 10: There many different types of EVBs and modules, but they are all based on three types of cell geometries. The dimensions and shapes varies greatly. Copied from [8].

Lithium Ion Battery Aging

Lithium ion batteries degrades as they age, meaning loss of power and capacity. The power loss is related to decreased conductivity between the materials in the cell, due to the build up resistive layers (solid electrolyte interface (SE) on the anode and solid permeable interphas (SPI) on the cathode), loss of active surface area and lowered mass transport. The capacity loss can be attributed to the lowered amount of cyclable Li+ in the electrolyte, by loss of electrode material, metal dissolution on the cathode and structural changes. Overall, the SEI layer is main contributor to aging and may also be very dangerous [23]. The SEI may be dangerous because dendrites can form, which can penetrate the separator causing internal shortcuts, resulting in thermal runaway [23, 54]. Dendrites can also grow due to overcharging, as a result of lithium ions plating rather than intercallating [13].

LIBs age continuously, even when not used. So called calendaring may be responsible for as much as 20-30% of the total degradation and is more severe when stored at high SOC and in elevated ambient temperatures. Otherwise, the causes for degradation are related to cycling [23]. The rate of degradation during cycling depends on cycle pattern, depth of discharge (DoD) and load.

	Anode	Cathode	Electrolyte
Capacity loss	• Structural changes	• Loss of active material • Metal dissolution	• Loss of cyclable Li+ to SPI and SEI
Power loss	• SEI formation • Metal Li+ plating	• SPI formation	• Decreased Li+ diffusion

Table 2: Causes of degradation, own illustration based on [23].

3.2 Lithium Ion Battery Outlook

Apart from the geometry, the cathode is generally what sets different types of cells apart. Historically, the most common cathode is the LCO ($LiCoO_2$). In recent years, other cathodes such as NCA, LMO, NMC, LFP has become increasingly commercially viable. See figure 11 for a cathode summary.

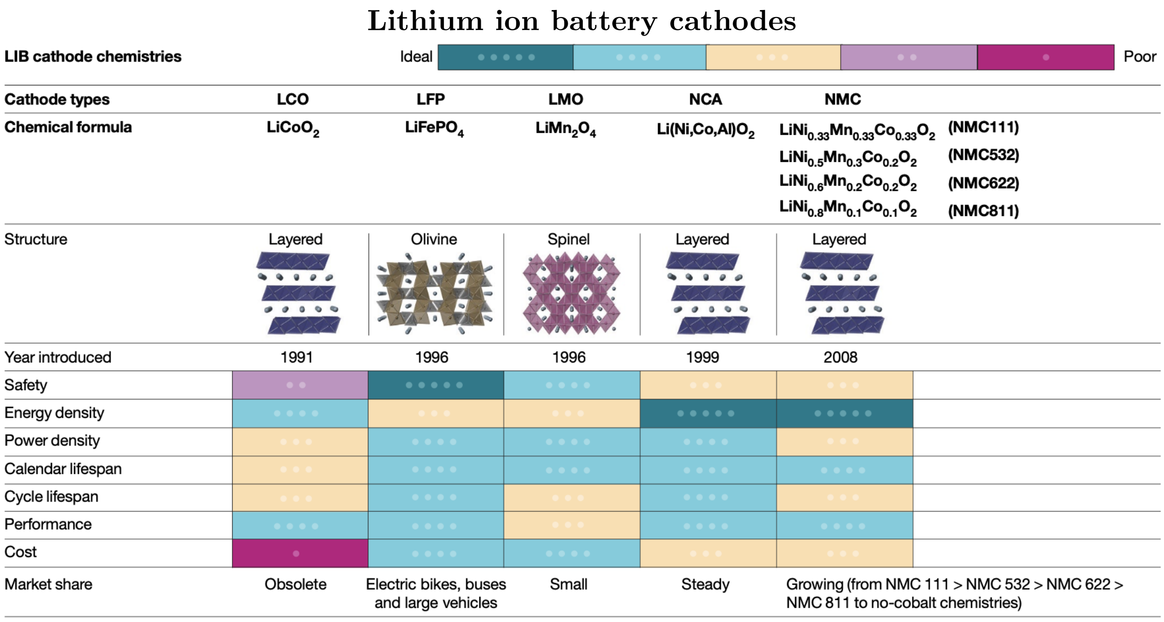

Figure 11: There are five major cathode structures, all with different characteristics [8].

As the world has opened its eyes for the ethics of mining cobalt (as a result of artisanal mining in the Democratic Republic of Congo), as well as high and volatile material prices, the chemistries has pivoted towards lower cobalt levels [4, 8]. The cobalt levels in different type of chemistries are illustrated in figure 12. NMC811 is projected to be the dominant cathode chemistry by 2024, see figure 13 [10].

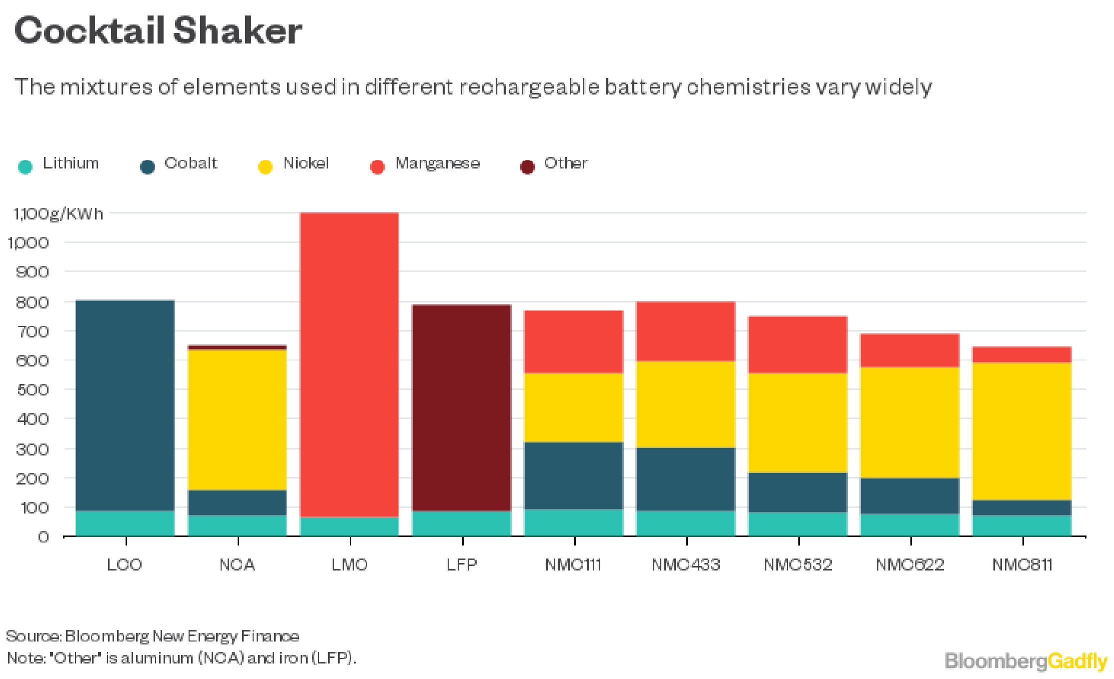

Figure 12: The mass per kWh for different type of chathode chemistries. Copied from [9].

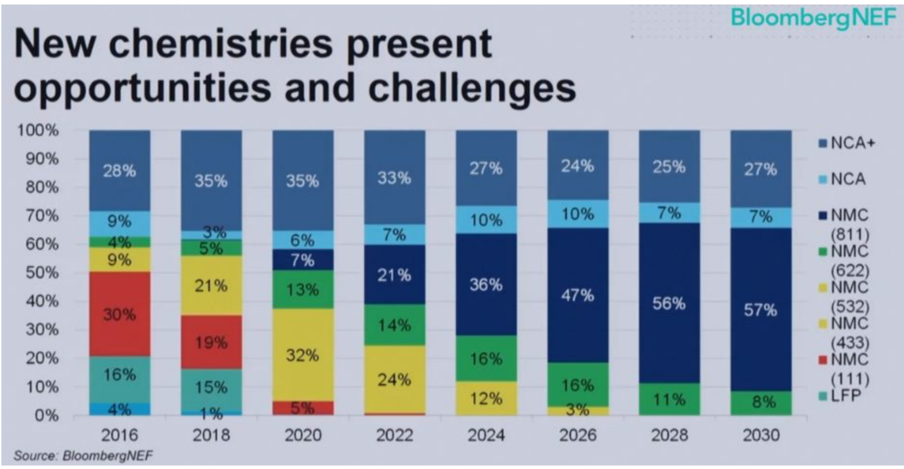

Figure 13: NMC811 is porjected to become the dominant cathode chemistry placed on market by 2024. Copied from [10].

Melin illustrates in figure 14 that LCO and LFP will be the dominant cathode chemistries reaching EOL until at least 2025. However, looking at the demand from 2000-2014 (figure 15), LCO and NMC were the primarily demanded chemistries, meaning they should be the dominant chemistries reaching end of life from 2018 and forward [11]. Melin calculated on cell mass and Avicenne on cathode mass, explaining the weight-difference. However, no explanation for the chemistry-difference could be found.

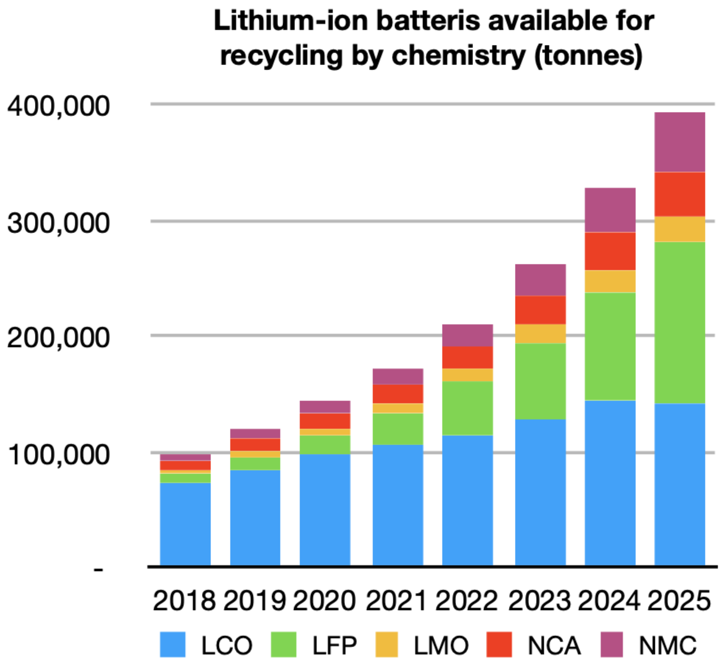

Figure 14: LCO and LFP will be the dominant cathode chemistries reaching EOL until 2026 globally [1].

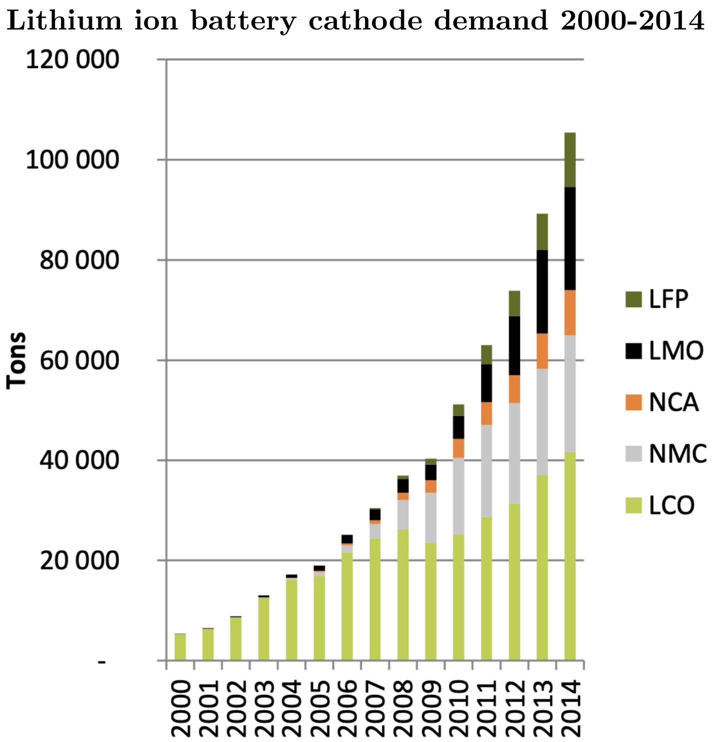

Figure 15: LCO and NCA should be the dominant cathode chemistries reaching EOL until 2026 [11].

RSQ: which type of chemistries will be dominant in the return flow? Why is there a discrepancy between new projections saying LCO and LFP will be dominant, while the demand in 2000-2014 was dominated by LCO and NMC?

3.3 The notion of low recycling rates

In 2019, the International Institution of Sustainable Development (IISD) claimed that "less than 5% of lithium-ion end-of-life batteries are recycled today" [55]. The same year, the World Economic Forum stated that the recycling capacity of lithium ion batteries is estimated to at least have grown by a factor of 25, to reach 54 % by 2030 [4]. This notion, that only a small fraction of lithium ion batteries are recycled today, is common. However, Hans Eric Melin, a renowned expert of lithium ion battery recycling, explains that this notion has become false over the years [2]. When referring to the 5 % recycling rate many paper cites the report by the NGO Friends of the Earth from 2013, in which they accredit the number to an interview with Umicore from 2012 [56]. The number thus comes from a time when there were few laptops, smart phones and electric vehicles that had reached EOL. Today already, the global recycling rate is rather 58 % [2, 37].

Nevertheless, the recycling rates are lower in Europe than globally. Only 45% all lithium ion batteries that reach end-of-life in Europe are recycled within Europe [26].

3.4 Risks associated with electric vehicle batteries

Risks associated electric vehicle batteries are many and dire. Firstly, faulty lithium ion battery cells can vent toxic gases and liquids and can in the worst case vent with fire or explode. Secondly, when many cells are assembled in a module or pack these the toxicity and thermal risks multiply, and there is also a risk of electric shock.

Thermal risks

The risk of thermal runaway is present throughout an EVB's entire life, even when driving or when parked, in varying degrees. However, at EOL, removed from the vehicle without a connected Battery Management System (BMS), the risks are much higher.

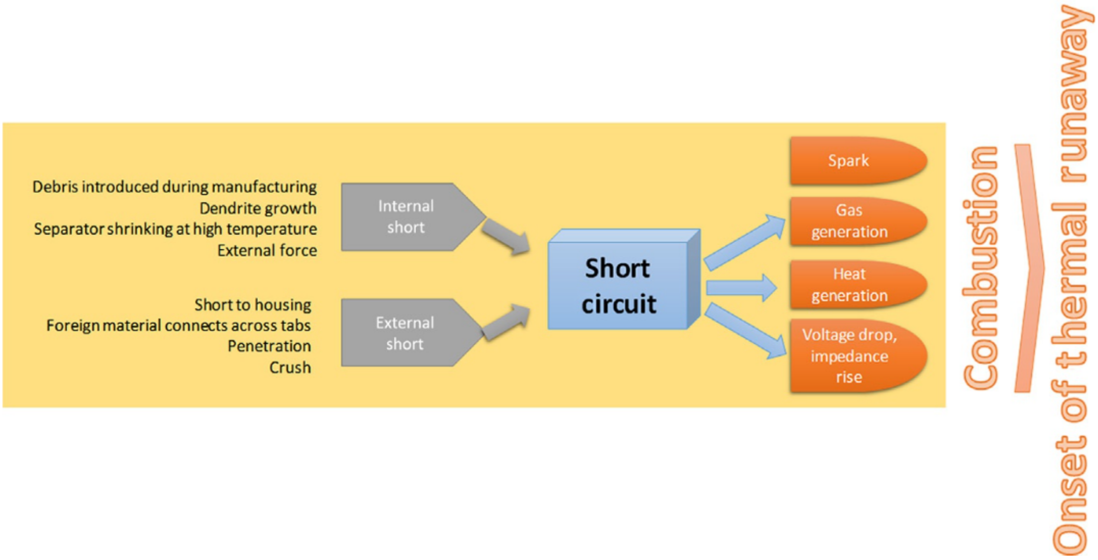

Figure 16: There are many reasons for thermal runaway. Copied from [12].

Thermal buildup is ultimately either a result of internal or external short circuit, and thermal runaway is mainly due to the exothermal reactions between cathode and electrolyte at elevated temperatures. As figure 16 explain, many reasons can cause short circuits, including cycling (ageing), mechanical deformation, ambient temperatures, over-charge and over-discharge [12, 23, 57]. The time before reaching thermal runaway depends on how much heat the cell has absorbed. Cells can smolder for more than an hour, but when a cell reaches 120 /C ([14]) or between 150-200 C [57] it vents with fire. If the temperature never reaches the threshold of 120 C, an eruption is dependent on an external spark that ignites the flammable gases emitted [14]. When venting with fire, the temperature reaches between 1000 to 1200 F (530 to 650 C) at a 12 inch (30 cm) distance, see figure 17.

Over time, the common problem that can result in internal short circuit is related to the solid electrolite interface (SEI), which naturally is built up as a coating on the electrode-electrolyte interface. It is necessary for normal performance, but it can grow too thick and develop dendrites. Dendrites is more prone to grow on the anode-electrolyte interface than the cathode-electrode due to the close proximity to the reversible potential ($0VvsLi/Li+$). Apart from normal cycling, the risk for dendrites is higher during overcharge and over-discharge as well as when charging during cold temperatures. These dendrites can penetrate the separator, causing a short circuit, see figure 18 [23, 57, 12].

The stored energy in a cell is made up of the electrical and chemical energy. The electrical is usually simple to measure as it is equivalent to the rating of the cell, measured in ampere hours (Ah) multiplied with the state of health (SOH). A standard 18650 cell usually contains 7-11 Wh (25-40 kJ) of electrical energy. The chemical energy is more difficult to measure, where the most common method oxygen consumption calorimetery. A standard 18650 usually contains 280 kJ. The amount of chemical energy is thus between 7 and 11 times larger than the electrical. In total, an 18650 cell contains approximately 300-320 kJ [13]. Hence, a Tesla model S with 100 kWh (364 MJ) battery pack contains between 2.5 and 4 GJ of chemical energy, adding up to 2.86-4.36 GJ in total. Roughly equaling one ton of TNT [58].

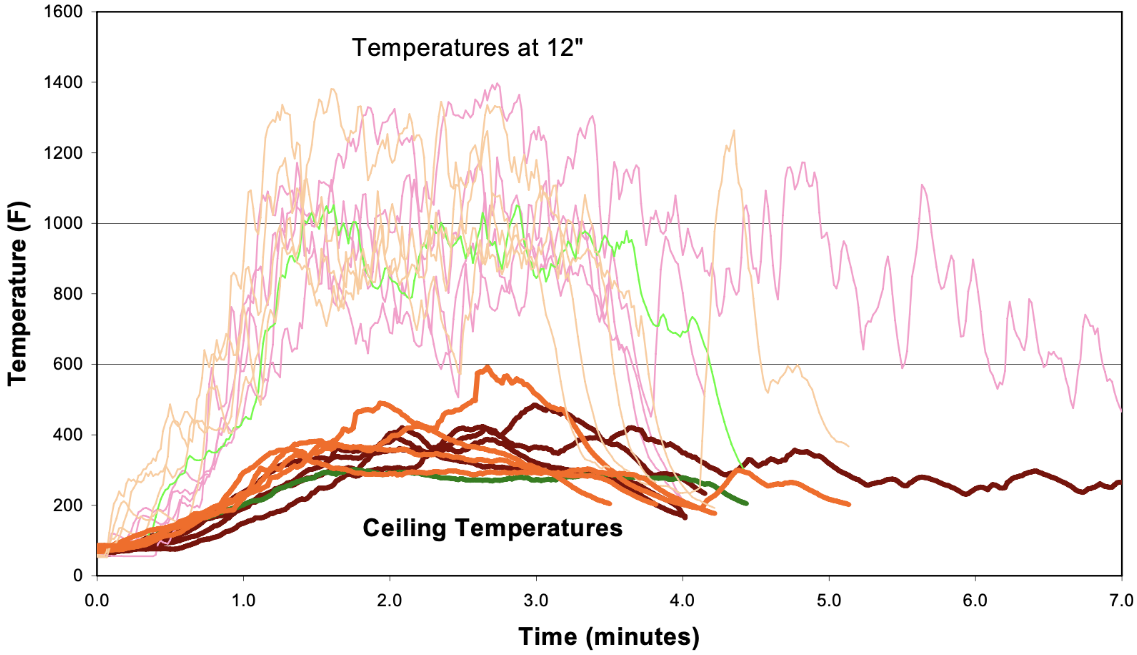

Figure 17: The peak temperature of a of LIBs venting with fire, measured in Fahrenheit and 12 inch from the chamber floor. Copied from [13].

Putting out a lithium ion batteries fire is very difficult. The main reasons is the fact that they are self-sufficient of oxygen, rendering suffocation worthless for fire suppression [12]. DNV GL conducted fire suppression tests on different cells in different constellations, for the Consolidated Edison and NYSERDA, and found that all extinguishers have benefits and drawbacks. Every tested extinguisher, including aerosol, could put out a flame from a LIB cell. However, in multiple cases, the flame reemerged when the extinguishing stream was stopped. They concluded that the ideal fire extinguisher should be both thermally and electrically insulating, of which water only fulfills the first criteria. Deionized water fulfills both criteria, but only until it is mixed with soot and ash from the cell which occurs almost immediately. In conclusion, the report recommends that if cell cascading (fire spreading from cell to cell) can be avoided, a gas may be used for fire suppression on a single cell. This is not the case for electric vehicle batteries, where applying "copious amounts of water" is the only recommended method [14].

RSQ: How are the thermal risks managed during storage and transportation of EOL EVBs?

Chemical risks

The toxicity of vented gases and leaked chemicals is high. The gases depend on cell chemistry and SOC, internal cell conditions such as temperature and pressure as well as external conditions. $LiPF_6$ is the most commonly used electrolyte salt and when it reacts with water (either as liquid or moisture in the air), hydrofluoric acid (HF) is formed. The toxicity tends to be higher when there is no venting with fire [57]. HF is a corrosive and lightweight gas, toxic to humans and can dissolve into water. Experiments have analysed the water used for extinguishing LIB fires and found that the concentrations of fluoride and chloride were above

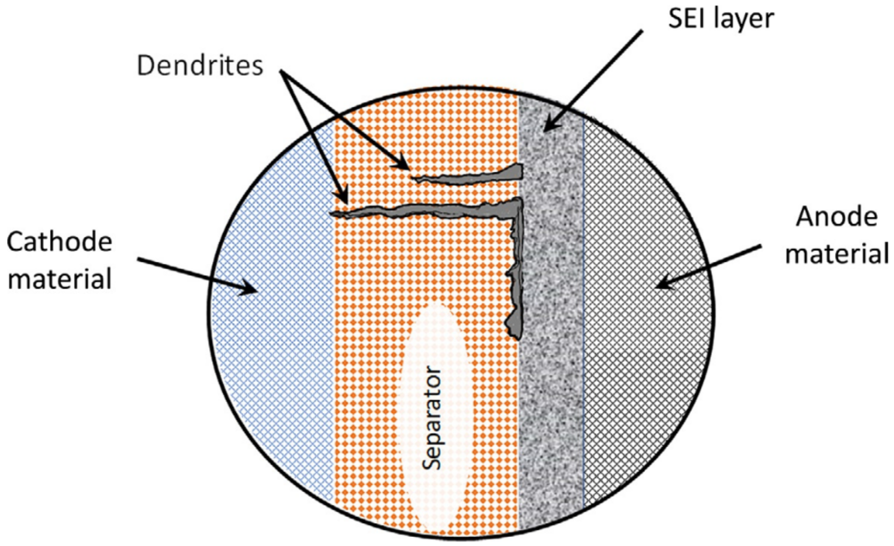

Figure 18: Dendrite formation on SEI may penetrate the separator, causing an internal short circuit. Copied from [12].

the limits for being allowed to be released directly into the environment [57]. Consequently, when a LIB fire is suppressed with water, the run-off water must be collected and sent to a treatment plant.

Carbon monoxide (CO) is also released when LIBs burn. It is a natural product of carbon based fires and thus also present when plastic burns, which there is a lot of i all types of vehicles. Henceforth, CO is prevalent when both an EV fire and internal combustion engine vehicle (ICEV) fire. Whether one of them is more dangerous is yet unknown [57].

RSQ: How are the chemical risks managed during storage and transportation of EOL EVBs?

Electrical risks

The voltage in electric vehicle batteries can vary between 300-850V [59]. As voltage is not dangerous per se, current is. Currents above 10 mA can cause painful to severe shock. Anything between 100 to 200 mA is fatal because of risk of atrial fibrillation.Currents above 200 mA clamps the heart so hard because of muscular contractions that the chances for survival are good [60]. However, these currents can cause burns that may be lethal if the they go through vital organs. Consequently, higher voltage does not directly equal higher risk. The current through the body from any electrical system is dependent on the resistance in the between the contacts, which varies depending on moisture, grip and pathway through the body. Unfortunately, the risk of shock is not eliminated after thermal runaway. As shown in figure 19, the cells may still be active even after a fire [14].

RSQ: How are the electrical risks managed during storage and transportation of EOL EVBs?

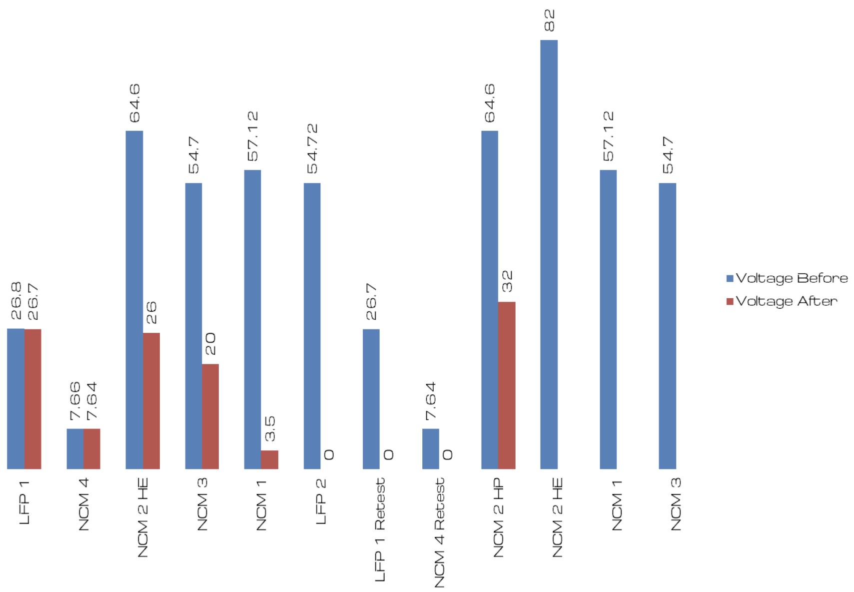

Figure 19: Cells may have residual voltage, even after fire tests, figure copied from [14]

3.5 The return logistics of electric vehicle batteries

Figure 20 illustrates the return logistics as described in previous literature. Following, the chapter is going through the steps in the return flow sequentially.

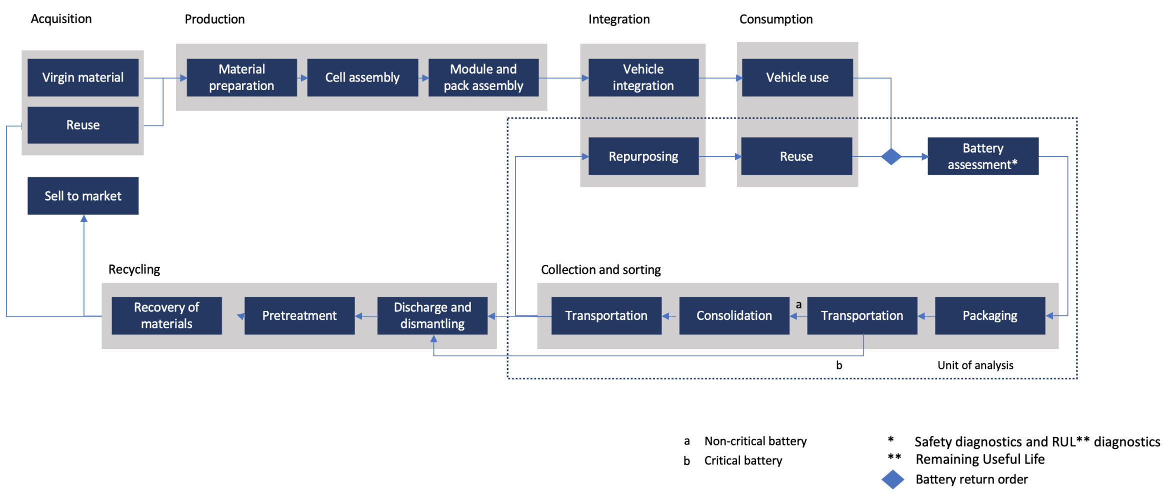

Figure 20: The return logistics of EVBs as known today. Figure adopted from [5] and [6]

The return logistics of EVBs has multiple actors with complex and ambiguous responsibility structures. Mapping out these responsibilities is fundamental in order to understand where to place a pretreatment plant. Following are the key stakeholders in the return logistics, found from initial interviews with the commissioning company.

- Automotive OEM

- Battery OEM
- Insurance company
- Car dealership/workshop
- Car dismantler
- Car owner
- Assessment company
- Packaging company
- Collector
- 3PL
- Remanufacturers
- Recycler

RSQ: Which actor is responsible for which part of the return flow today?

RSQ: Who owns the EVB in the different stages in the return flow, and where does the ownership change?

RSQ: Will the vehicle owner get reimbursed in the future, when selling the vehicle to a car dismantler/remanufacturer?

Entering the return flow

Batteries can reach end of life either after capacity loss or after being damaged, where the latter (defective batteries, recalls and accidents) is the most common reason today. 50-60 % of all returning EVBs in 2019 were either damaged or critical due to a accidents or production issues. Nevertheless, it is expected that 98% of all EOL EVBs will be non-critical (see definition in chapter 3.5) [5].

The first step is extraction of the battery, where a high voltage expert has to be involved. When the battery is extracted, Ziemba *et. al* identified two types of orders that initialize an EVB's return flow. The first way is a so called spot business order. When the electric vehicle arrives at the dealership, the battery is removed and an order is sent to the a recycler or collector on the spot. The second way is to have a contract with a collector or recycler. Sometimes the collector has a packaging box stored at the dealership, to pick up when needed [5].

Both ways are prompted by the dealership contacting a collector to remove an extracted EVB. Some specific information has to be provided in the order, for example address, weight, volume, packaging and the battery state. The condition of the battery is by far the most important because it determines the transport method. Still, sometimes the battery is transported to a warehouse without a diagnose [5].

RSQ: Which part pays for the storage and transportation of the battery?

RSQ: The OEM has producer responsibility for the battery disposal but does not own the battery anymore. How does the OEM pay for the disposal?

Battery assessment

Batteries degrade, see chapter 3.1, and is usually assumed to reach end of life at 80% SOH. However, this assumption is not sufficient when determining the return flow path. Following paragraphs go through different key parameters and their respective analytical methods relevant for determining the return flow.

Diagnosis State of Safety (SOS) Every electric vehicle battery's condition, or state of safety (SOS), must be checked by a certified dangerous goods expert before transportation. [5]. The condition reflects the state of degradation, sometimes called State of Safety (SOS) [54]. There are various ways to grade the conditions but the most common ones are; non-damaged, damaged and critically damaged, also referred to as green, yellow and red [61]. EUCAR, established 1994 with global automotive OEMs as members, has developed their own hazard levels described in figure 3, however they classify the SOS on cell level and not on pack level.

Level	Description	Classification criteria and effect
0	No effect	No loss of functionality.
1	Passive protection activated	Cell reversibly damaged. Repair needed.
2	Defect	No leakage. Cell irreversibly damaged. Repair needed.
3	Minor leakage or venting	Weight loss <50% of electrolyte weight.
4	Major leakage or venting	No fire or flame. Weight loss $\geq$ 50% of electrolyte weight.
5	Rupture	No explosion, but some internal parts are expelled.
6	Fire or flame	No explosion.
7	Explosion	Explosion (disintegration).

Table 3: EUCAR hazard levels for battery safety tests and description [24]

A non-defective (green) battery must have passed the tests according to UN38.3 and be fully functional. As defined in ADR SP376, a defective (yellow) battery is damaged or defective such that they do not conform to the type tested according to UN38.3 [61, 43]. A critically defective (red) battery is "liable to rapidly disassemble, dangerously react, produce a flame or a dangerous evolution of heat or a dangerous emission of toxic, corrosive or flammable gases or vapours under normal conditions of carriage". If the battery state is unknown it must be regarded as defective [5, 43].

Standard methods and technologies for condition diagnosis is yet to be established. Today, there are several methods, which in combination are used to set a state on cell level. Some of which are, visual inspection to identify any scratches or bumps, visual inspection of swelling over time, temperature increase measurement over time and measuring cell voltage [6]. It has proven very difficult to determine the condition on cell level; internal problems such as dendrites are not revealed at visual inspection and voltage loss naturally follows degradation. The dendrites may also grow without cycling, why battery packs that has remained on a shelf for a while without a problem can burst into flames when moved [5]. All of these problems are increased as the batteries contain more cells. Analysing hundreds or thousands of cells in an EVB will need new technologies and methods.

RSQ: Which part is responsible for the certified battery analyst to check the SOS of the battery?

RSQ: Are there any promising methods on the horizon that accurately can analyse the SOS of large battery systems? When are they commercially available?

Diagnosis of Remaining Useful Life (RUL) The value of an EOL EVB is based on the material and the Remaining Useful Life (RUL). Determining the RUL is fundamentally the same as determining the area under the graph above a certain threshold (SOH_{min}) in figure 3. To determine the RUL, the battery must first be characterized, which can be done using multiple methods. Barai *et. al* compares some non-destructive methods in a review about the various international standards and regulations for the characterisation of lithium-ion cells including electrochemical impedance spectroscopy (EIS), differential voltage analysis (DVA) and incremental capacity analysis (ICA) [62]. Yang *et al.* explore the perks of using machine learning for determining RUL. Conventional methods are backpropagation (BP) algorithm and support vector machines (SVMs), both of which are feedforward artificial neural networks (ANNs). The review found that a hybrid between physical modeling and data driven modeling produced more accurate predictions than the conventional methods. In Yang's method "relevant vectors obtained with the selective kernel ensemble-based relevance vector machine (RVM) learning algorithm are fitted to the physical degradation model, which is then extrapolated to failure threshold". Nevertheless, these kind of diagnosis has only been demonstrated on cells, not on electric vehicle battery systems, although Yang's paper concludes that it very well may be implemented in Battery Management Systems (BMS) [3].

RSQ: Which part is responsible for checking the RUL of the battery?

RSQ: Are there any promising methods on the horizon that accurately can analyse the RUL of large battery systems? When are they commercially available?

RSQ: How does the battery RUL assessment influence where an EVB is going today?

RSQ: How much of the RUL can be extracted from the vehicle's own monitoring system? Is this done regularly?

Collection

In Europe, all batteries in consumer goods are collected by collectors, most of which are included in the European Association of National Collection Schemes for Batteries, EUCOBAT. Traditionally, with portable batteries in consumer goods, the collectors collect the batteries through networks of pick up points at convenient places to make it easier for consumers to return waste batteries [63]. With EVs, the consumers can not be expected to manage the delivery of the battery to the pick-up-points. Therefore, the recyclers have their own logistics network and work closely with third party logistics (3PL) [5]. All collectors work within collection schemes, which are country specific.

RSQ: According to the Battery Directive, the producers (automotive OEM) is responsible for the disposal of the batteries, how does this work in the real world?

RSQ: What is the difference between an EV reaching its EOL in a dealership and at a car dismantler?

RSQ: Collectors mostly play a part in the collection of portable batteries. What part do they play in the return flow of EVBs?

RSQ: Which part is responsible for the storage and transportation of the battery?

Packaging If transported on road the ADR (covered in chapter 3.8) determines the required packaging method. Lithium ion batteries are considered grade 9 dangerous goods in ADR.

(a) (b)

Figure 21: Example of the type of packaging solution for a red (a) and a yellow (b) battery from [15, 16]

As described in chapter 3.1, EVBs are also large and heavy. These characteristics of an EVB makes packaging challenging. Depending on the SOS, different packages are suitable.

Red batteries must be packaged in certain safety boxes regulated by P911 (if $<$ 400 kg) or LP906 (if $>$ 400 kg) in the ADR. Generally, these boxes must be able to extinguish a fire, filter the toxic fumes and contain leakage. The outside must never exceed 100 C. Safety boxes are therefore very costly, between 10,000-25,000 € per container. An example of a safety box is shown in figure 21a.

Yellow batteries are often transported in less sophisticated boxes made out of wood or plastic. The battery must first be placed inside an impenetrable plastic bag, surrounded with fire-suppressing and chemical-absorbing material (often Vermiculite or sand), which then is placed inside a package suited for yellow batteries, exemplified in figure 21b.

Green batteries are regulated by P909, P903 or LP903 in the ADR. P909 states that batteries may be transported ”unpackaged or on pallets when the cells or batteries are afforded equivalent protection by the equipment in which they are contained.” [43]. An EVB might be considered equipment for all contained cells. P903 states that a battery weighting over 12 kg with a ”strong, impact resistant outer casing”, need no certified packaging [43]. Unfortunately, no clear definition of strong has been established yet [64]. Still, no diagnostic technology can verify a green battery with confidence, and therefore almost all batteries are transported as yellow. Logistic companies that transport an EOL EVB can buy the boxes, but charge their customers for it [5].

RSQ: Are there packages specifically designed for large EVBs? Or must the EVB be disassembled before transportation?

RSQ: Some experts claim that LIBs requires acid-proof transportation because leakage may result in harm to human health and to the environment. How does this comply with the

Storage Storage of EVBs is highly regulated in practice bet varies greatly depending on local authority. The allowed distance between stored EVBs can be anything from 2 to 6 meters and only 2 packs are allowed to be stacked, with a minimum of 1,2 meters in between. During storage, the SOS may change and precautions must be taken to deal with an eventual emergency [5]. According to internal knowledge at the commissioning company, there are no official regulations but the ones mentioned above are all set up locally [6].

RSQ: From where will storage safety regulations come, and when?

Transportation Transportation is can be separated into two flows; transportation to directly to recycling or second use, or via a consolidation point. Via a consolidation point is preferable, where the first stretch is called primary collection and the second part is called secondary logistics, see figure 22. To increase volumes, most batteries are transported to a consolidation point where batteries accumulate. If the consolidation point is full or if the battery is critical, it is sent directly to recycling [5].

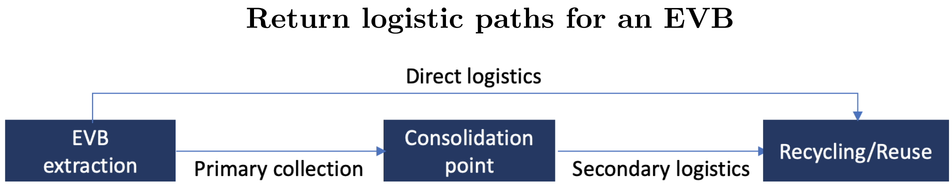

Figure 22: A battery can either be sent to recycling or second use directly or via a consolidation point. If the consolidation point is full, or the battery is critical it is transported directly, otherwise via the consolidation point. Figure adopted from [5]

RSQ: Is there a trend towards more transportation by train as it is more sustainable?

RSQ: Where are the battery consolidation points located? How do they look like?

3.6 Lithium Ion Battery Pretreatment Methods

Pretreatment is the first step to recover the battery material. Maximizing recovery of valuable materials, reducing the downstream material flow rate and ensuring the safe handling of spent LIB are the key objectives.

The reduction of material flow is important because of the high costs of transportation of spent lithium ion batteries, sometimes making up to 40-50% of the overall recycling cost. These costs, are mainly due to the fact that LIBs are dangerous goods (see chapter 3.8). Hence, producing black mass is important because it may lower the transportation costs while increasing safety. Two types of loads are commonly received at pretreatment plants; bulk shipment of portable batteries from consumer goods, or battery packs [18]. Following are the pretreatment steps, also illustrated in figure 23. However, as illustrated in figure 24, the process routes vary greatly depending on manufacturer.

- Sorting by chemistry
- Battery pack disassembly
- Stabilization
- Comminution
- Electrolyte recovery
- Material separation
- Binder separation
- Thermal treatment

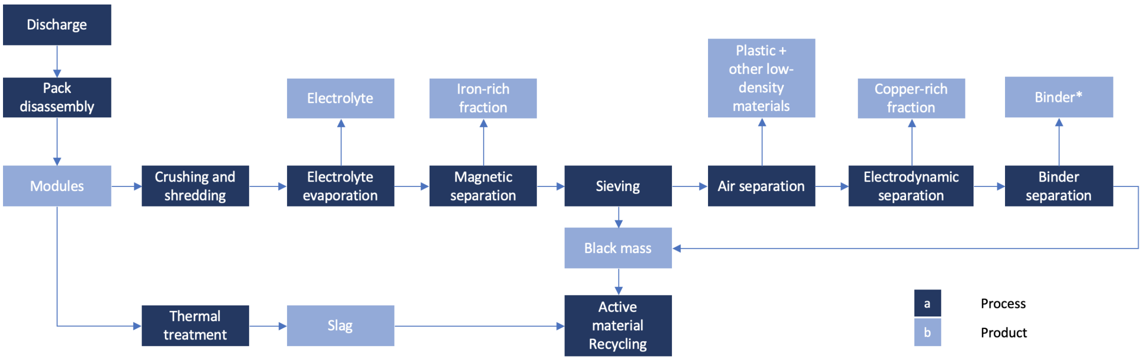

Figure 23: Pretreatment process. Modules are either thermally treated with a resulting slag going to further recycling, or crushed and separated into black mass, going to further recycling. Adopted from [17, 18, 19]. *Binder separation has only been found in [18].

RSQ: Packaging for transportation is dependent on a number from the list of waste. How is black mass classified with a UN number? Must this be done for every batch?

Sorting The pretreatment process can either be chemistry specific or non-specific. The non-specific process can process a broad range of batteries via thermal treatment that produces a slag which can be used for further treatment. These methods can not recover all materials. The chemistry specific method, separates the materials in multiple steps ending up with a high-value black mass. Only the chemistry specific processes allows lithium recycling and can produce battery grade material [19]. This thesis is continuously focusing on the chemical specific process. To optimize the specific processes, the batteries must be sorted by chemistry.

Stabilisation Stabilization processes are necessary avoid strong temperature increase, the release of hot, toxic and corrosive chemicals, and the loss of potentially retrievable components such as electrolyte and plastics to combustion the during comminution (crushing and shredding) [20]. Wuschke *et. al* states that discharging to 0% SOC is necessary, which generally can be done using electrical discharge or ionic self-discharge (solution discharge) [65]. Sommerville *et. al* provides more stabilization processes; thermal treatment, cryogenic treatment, electrolyte extraction and in-process-control (see figure 25) [20].

Electric discharge is relatively quick and controlled and allows for energy recovery. However, it is difficult to scale with current technologies as hardware and software barriers such as the BMS and broken fuses must manually be bypassed.

In solution discharge the battery is submerged in a salt-solution and is let to slowly discharge. It may prove to be more scalable than electrical discharge as it requires less oversight. However, because nothing is connected to the battery, SOC can not be determined leading to long, precautionary discharge times. Furthermore, 0 % SOC does not necessarily mean the OCV is 0 V, but can be anywhere up to 3 V meaning measuring the OCV post-discharge might be necessary [20]. Solution discharge does not directly allow for energy recovery, but as the solution is heated up, the energy could potentially be recovered using heat pumps.

Cryogenic methods means the cells are cooled down to solidify the electrolyte (for example

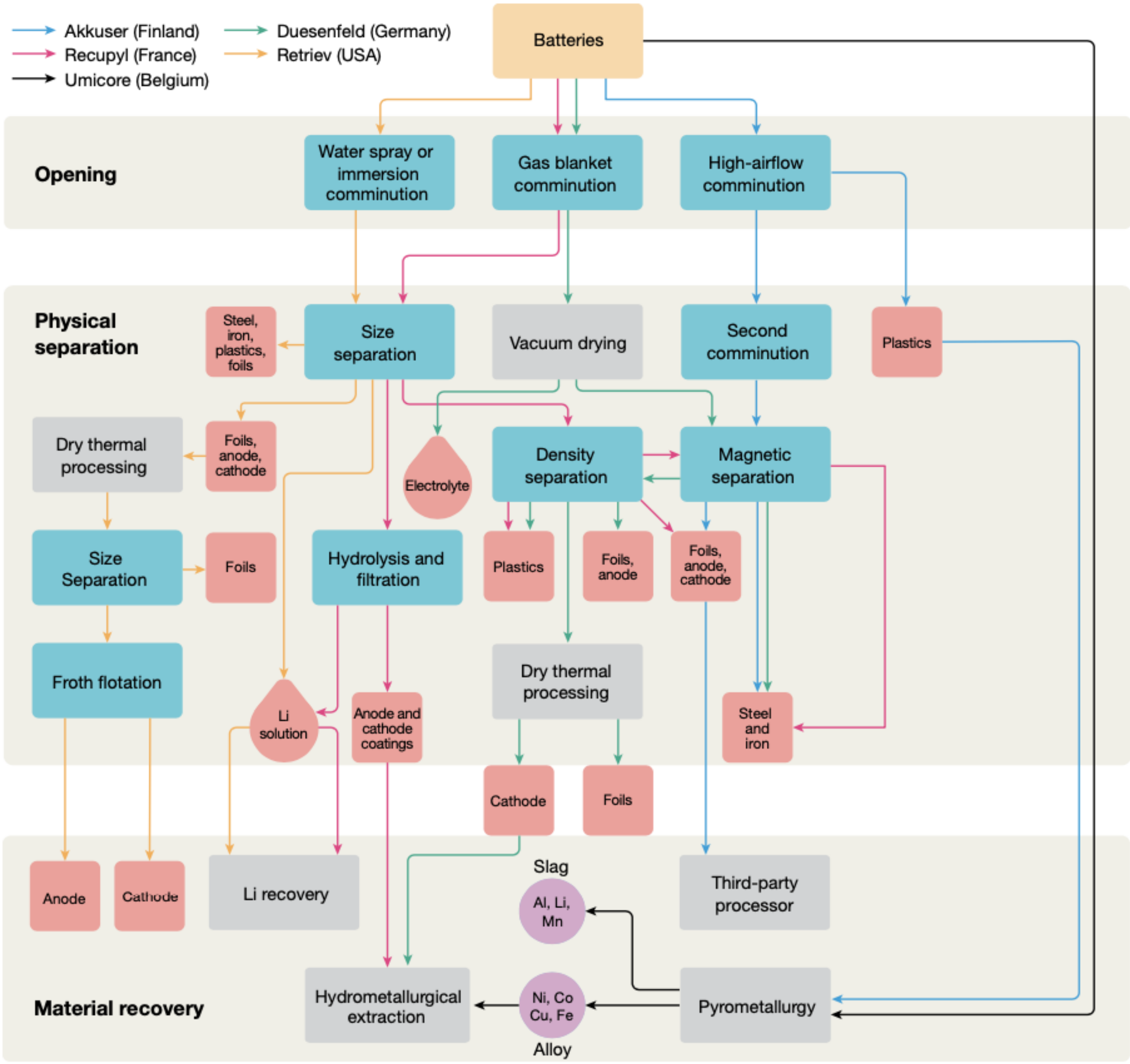

Figure 24: A flow chart of the recycling methods used by different recyclers [8]

by using liquid nitrogen). By using cryogenic methods during comminution, the binders are kept below the glass transition temperature, at which it is brittle improving the downstream separation technique. However, this method is expensive and energy intensive and does not scale well [20].

Thermal treatment can be done in multiple ways. One method is to heating up the cells to 100-150C for ca 1 hour prior to comminution. One could also heat up the cells to 300C if its done in a nitrogen atmosphere. First the batteries must be discharged to avoid risking thermal runaway. Pyrolysis, heating up the cells to 400-600C to remove the electrolyte, binder, and separator has also been tested. Pyrolysis creates challenges with gas containment, but allegedly makes the comminution faster [20].

Finally, in-process-control limits risks by performing comminution by inhibiting thermal runaway and prevent loss of material to gaseous byproducts of combustion caused by thermal runaway. The methods are either to comminuting under an aqueous spray (water or LiOH) or in an inert gas. The aqueous spray is a cheap method to significantly reduce the risks for thermal runaway but the waste water needs further cleaning processes and also produce hazardous HF gas as LiPF6 reacts with the oxygen. The inert gas does not wet the materials and does not create any waste product, but is expensive and does not stop a fire once started. [20]

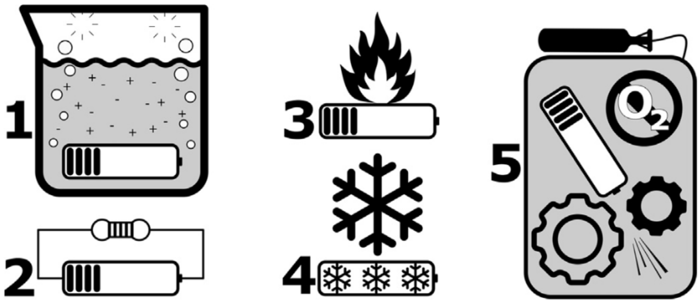

Figure 25: Five methods to stabilize a battery before comminution [20]

RSQ: How long does it take to discharge battery to 0% SOC?

Battery pack disassembly EVB disassembly requires qualified technicians and tools. In the conflict of interest between design for manufacturing (DFM), design for performance (DFP), and design for disassembly (DFD), the two prior have been superior. Therefore, the cells, modules and packs vary greatly in structure and geometry making disassembly time consuming and difficult to automate [19, 20]. Sometimes the cells are disassembled too; first the cell is opened using saws, sharp blades or lasers, after which the components are sorted into packaging, electrolyte, separetor and electrode [20]

To ameliorate vehicle disassembly across brands, the International Disassembly Information System (IDIS) was developed in 1990 [66]. It contains disassembly guides for 3219 vehicle models and variants from 78 different brands. Information in IDIS is submitted by the OEMs, and is not reviewed by any other organisation [67]. Nevertheless, IDIS has no official dismantling guide for EVBs yet.

RSQ: How much must the EVB be disassembled before crushing? How much is manual labor and how much can be automated?.

RSQ: How is dismantling regulated?

Comminution The term comminution means to reduce to powder, and is commonly used in the literature. Comminution can be done by applying shearing, cutting and tearing stresses on the material trough for example automated rotary comminution techniques. The combination of these stresses at low speeds (circumferential velocity < 5 m/s) is recommended for non-brittle metal scrap such as batteries, but there is not standard process [65, 20]. Wuschke *et. al* determines a strong correlation between temperature increase and SOC ($Temp = 3.32SOC + 19.19, R^2 = 0.99$). The lower SOC the lower temperature increase. Yet, the cells should optimally be at 0% SOC at comminution, as 2% SOC increased the temperature by 27C. As batteries experience a rebound effect and retain a voltage after full discharge, this cause complications with keeping short circuits post-discharge. Furthermore, the peak temperature was found 20 seconds after comminution, meaning the highest risk for fire is in downstream process (local transportation, storage, screening etc.) [65].

The input greatly influence the purity of output, which in turn greatly influences the downstream separation processes. Sorting is important to avoid intimate mixing of different battery components which is important for the purity of recycled material. Automation of comminution requires automated determination of the cell types and their materials [20].

RSQ: What throughput does the crushers and shredders have?

Electrolyte recovery Some researchers claim electrolyte recovery is the most important challenges in LIB recycling [18, 68]. He *et. al* manufactured an aqueous exfoliating and extracting solution (AEES) to separate the electrolyte from the electrodes. Via distillation and filtration, the electrolyte, made up by ethylene carbonate (EC), propylene carbonate (PC) and $LiPF_6$, could be recovered at a 95.6% efficiency [68]. Despite the suggested importance of this process, however, only a few pretreatment pilot plants and research papers on the processes and methods have been found [18, 68, 69].

RSQ: Can the electrolyte be recycled or reused? If not, how is it disposed of?

Material separation To create homogeneous waste streams after comminution, the material can be subjected to a range of different separation processes that exploit property variations. Magnetic separation can remove steel casing and other ferromagnetic materials. Sieving, density separation and electrostatic separation can remove the separator and other packaging material. Then, to achieve higher purity waste streams needed for further material recovery, density and hydrophobic separation including different flotation processes can be used. The remaining material, black mass, should consist of only the electrode materials [18, 8, 20, 70] .

RSQ: How well can the materials be separated at scale? How is the black mass quality and yield dependent on throughput?

RSQ: Can the pretreatment plants receive all types of electric vehicle batteries?

RSQ: Are the processes energy intensive? How much should the electric energy mix be considered when placing a pretreatment plant?

RSQ: How is the quality and yield of black mass dependent on the homogeneity of the battery types?

3.7 End of Life Vehicle whereabouts

De-registered vehicles without a Certificate of Destruction (CoD), available information whether its been exported or treated in an Authorised Treatment Facility (ATF), are referred to as vehicles with unknown whereabouts (VUW). According to the European Commission's assessment on the ELV directive, vehicles with unknown whereabouts numbers 4.6 million vehicles in Europe in 2014 (see figure 26). This makes up 30-40% of all end of life vehicles (EVLs) [21]. Reporting on intra-EU trade is based on data from traders, rather than customs, and is therefore "very incomplete". The conclusion of the report stated that "monitoring ELV Directive enforcement at a national level is currently not possible and needs additional data.

In particular, it is not known by most national authorities if all ELVs generated within the country's territory are treated according to the requirements of the ELV Directive" [21].

The failure to demonstrate compliance with the ELV directive, according to the report, is firstly due to; European member states not being able to track vehicles well. The responsibility for accurately documenting intra-EU trade is inconclusive. Furthermore, because there are no legal requirements the vehicle owner does not need to submit any export documents or CoD, resulting in several member states losing track of vehicle owners. Secondly, illegal operation of dismantling is lucrative. There are reportedly a high number of illegal non-certified dismantling operators. In 2015, inspections found 1000 in the UK and 500 in France. Thirdly, lack of incentives to return ELVs to collection points or ATFs, which is the main contributor to statistical gaps, and numbers from Germany's scrapping premium in 2009 show that good incentives can increase the ELV return by a factor of 4.5 [21].

EU-28 balance for registration of new and import of used vehicles, the change in the vehicle stock and the whereabouts of the vehicles [21]

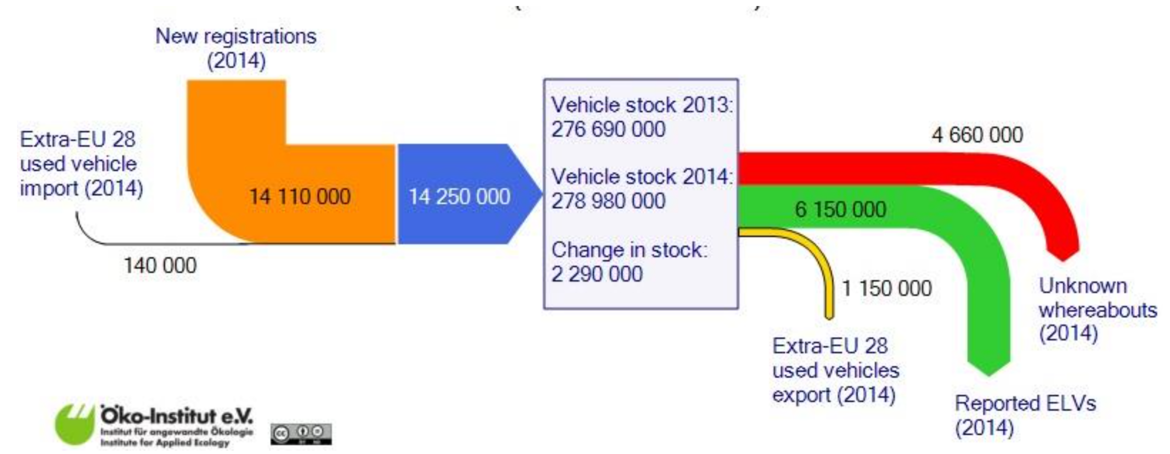

Figure 26: In 2014, 4.66 million end of life vehicles were had unknown whereabouts. Similar numbers were at the time of report expected for 2015 [21].

Despite the data is unreliable according to the authors, Poland seem to be the main importer of vehicles, with a majority of vehicles aged above 13 years 27. Why Poland is uniquely good at reporting data, or why they have so many imports is unknown.

RSQ: Will the number of VUWs decrease for EVs because of their often-accompanied high technology systems? How does increase traceability on modern vehicles go along with GDPR?

RSQ: How will the lack of charging infrastructure influence the whereabouts of ELVs?

3.8 Regulations and Directives

Regulations are binding legislative acts for all EU members, directives are targets that EU members must achieve and decision are only confined to the addressed members [71]. Europe has multiple regulations and directives on how to transport lithium ion batteries and black mass. Their being multiple, outdated and up to interpretation, however, is problematic [55].

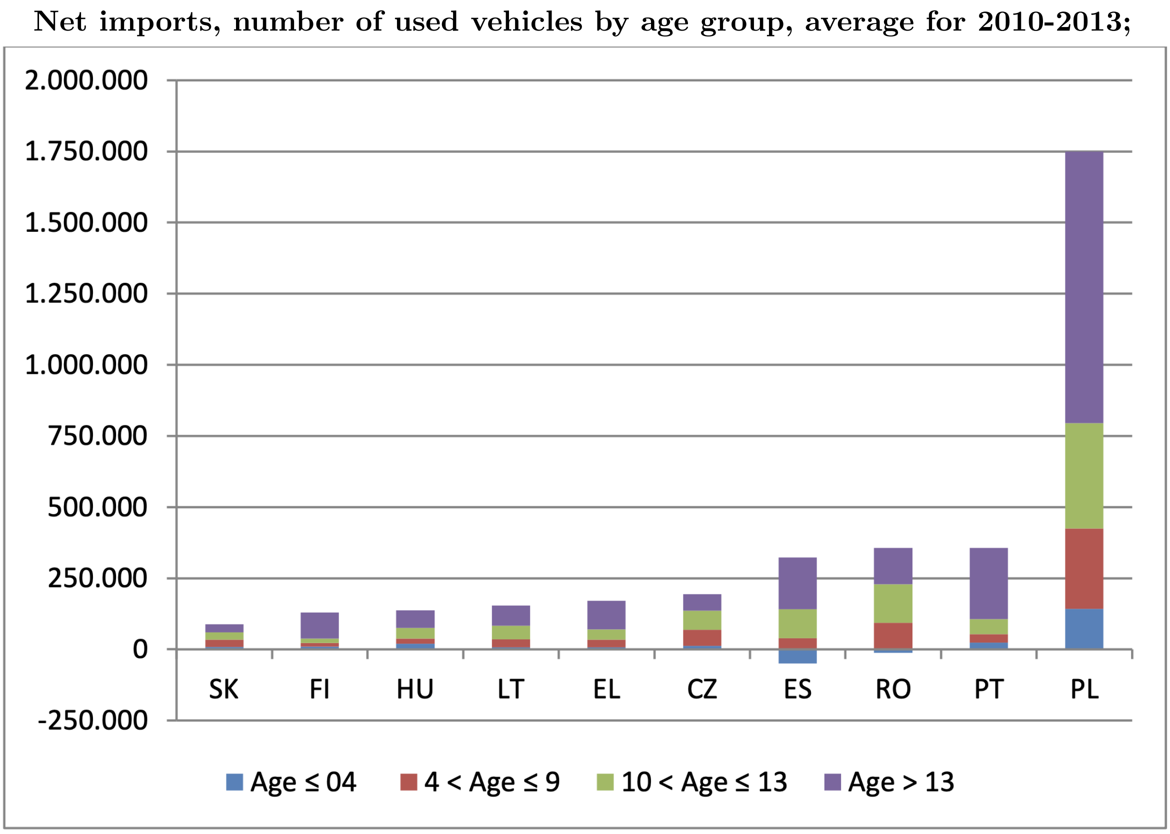

Figure 27: Poland is the country in Europe with the highest numbers of imported vehicles with almost 1 million vehicles aged over 13 years [21]

Basel Convention

In 1989, the UN Basel Convention was adopted internationally to "protect human health and the environment against the adverse effects of hazardous wastes, household wastes and incinerator ash". It defines waste as "substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law" [72]. The convention defines the disposal methods as resource recovery, recycling, reclamation or reuse, however, these processes are not defined further. The lack of definition, understanding on the nomenclature (difference between reuse, remanufacturing, repurposing and recycling), national interpretations has led to unquestioned, inefficient and uncoordinated recycling processes [55]. In Sweden, the penalty for illicit transportation of waste is fines or imprisonment of a maximum of two years, as defined in the the Swedish environmental code's 6th section, 29th chapter and §4a [73].

RSQ: How does the Basel Convention affect the transportation of EOL batteries within Europe?

European list of waste (ELW)

The commission Decision 2000/532/EC acts as a reference list for all types of dangerous goods. According to the European Commission it "provides an EU-wide common terminology for waste classification to ease waste management, including for hazardous waste. The assignment of ELW codes serves in a broad variety of activities, including the transport of waste, installation permits (which often refer also to specific waste codes), or as a basis for waste statistics" [74, 75]. The ELW was revised in 2014 and 2017, and in 2018 a commission notice on technical guidance for the WFD and the ELW on the classification of waste was published [76].

In the ELW, lithium ion batteries are categorised as "other batteries (160605) and are considered as absolute non-hazardous (ANH). Evaporated electrolyte (160606*) is considered being absolute hazardous (AH).

Battery Directive

Directive 2006/66/EC is also called the battery directive has been the "most influential piece of legislation, restricting the disposal and mandating extended producer responsibility (EPR), under which producers are responsible for the costs, collection and recycling of batteries when they become waste" [77]. Its primary objective is to "minimise the negative impact of batteries and accumulators and waste batteries and accumulators on the environment, thus contributing to the protection, preservation and improvement of the quality of the environment" [38].

It has grown outdated, as it excludes lithium ion batteries and other evolving chemistries and is unclear regarding inherited producer responsibility when it comes to remanufacturing. It is currently being updated by the European Union, with an expected release late 2020 [77].

Waste Shipment Regulation (WSR)

The waste shipment regulation (WSR), EC No 1013/2006, defines how waste should be shipped and makes the Basel Convention into EU law [76]. Articles 34 and 36 states that the export of waste for a disposal operation outside the EU/EFTA area is prohibited, as well as the export of hazardous wastes from the EU to any non-OECD Decision country [78].

In 2016, the commission implementation regulation (EU) 2016/1245 was implemented, which sets out a ”preliminary correlation table between customs and waste codes. This correlation table is intended to step up the enforcement of the Waste Shipment Regulation whereby customs officials will be able to identify potential waste streams more easily. The table will thus serve as a tool to assist in curbing illegal exports of waste out of the EU” [79, **?**, 21].

Battery handling and storage regulations

Few handling and storage regulations were found. However, according to the Swedish Waste Code 2011:927 §26 (not official translation), anyone who professionally handles waste that contains or consists of batteries must ensure that

1. the storage and management of the waste in a treatment plant takes place in suitable containers or in a place which is provided with a dense, hardened surface and is protected against precipitation, and
2. the waste is not incinerated or disposed of without
   (a) liquids and acids have been removed from the batteries to be disposed of separately from other battery waste; and
   (b) the measures have been taken that are possible and appropriate to achieve the goals for special disposal and recycling set out in section 8 of the Ordinance (2008: 834) on producer responsibility for batteries.

Waste Framework Directive (WFD)

The directive waste framework directive, 2008/98/EC, acts as a baseline for waste. According to the European Commission it ”sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, recovery. It explains when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products” [80, 81].

The WFD was amended in 2018 by 2018/85 directive, re-enforcing and increasing the targets of the WFD. It ”sets long-term objectives for the Union’s waste management and gives economic operators and Member States a clear direction for the investments needed to achieve those objectives”, and emphasises the importance of data tracking though electronic registries. Furthermore, it revokes the member states to submit a report every three years, and replaces the compliance monitoring with a yearly based on data which is reported to the Commission. It too clarifies the definition of material recovery as ”any recovery operation, other than energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy. It includes, inter alia, preparing for re-use, recycling and backfilling” [82].

RSQ: When are electric vehicle batteries considered as waste?

European agreement concerning the international transportation of dangerous goods by road (ADR)

The European agreement concerning the international transportation of dangerous goods by road (ADR) constitutes the regulations for transportation of dangerous goods by road in Europe and a few other countries. It is made up of two annexes; Annex A regulates the goods, their packaging and labels and Annex B regulates the construction, equipment and the operation of the transporting vehicle [83]. It is updated every two years, with the latest published in 2019.

According to the ADR, lithium ion batteries are considered dangerous goods of class 9 and must be transported accordingly [43].

Depending on multiple variables, including shipping condition (as cells, batteries, contained in equipment, packed with equipment), point in life cycle (prototype, new, waste), condition (non-defective, defective, critically defective), 35 different regulations are suitable, see figure 28. Within these 35 regulations, further specifications depending on weight and capacity narrows down the method of shipping even more.

Generally, non-critical batteries are regulated by P903 (if $< 400kg$) or LP903 (if $> 400kg$) or by P909 if its transported to recycling and the origin is unknown. Defective batteries are regulated by P908 (if $< 400kg$) or LP904 if (if $> 400kg$). Critically defected batteries are regulated by P911 (if $< 400kg$) or LP906 (if $> 400kg$) [43].

In Sweden, anyone who intentionally or through gross negligence violates section 2, first paragraph, shall be sentenced to a fine or imprisonment for a maximum of one year [84].

RSQ: How is the ambiguity between the different regulations affecting the return flow?

Labeling Directives

Labeling is important to promote traceability and correct handling, and prevent heterogeneous return flows and thus cross-contamination in the recycling processes. However, the literature research has resulted in no clear labeling standards that are widely used.

In 2012, the Battery Recycling Committee of the Society of Automotive Engineers (SAE) wrote a report on recommended practice on for labeling electric storage devices [85]. In 2013, they published report on a standard label for rechargeable batteries [39, 86]. In 2016, they published a "Battery Identification and Cross Contamination Prevention" document, that provides information for a system that sorts all types of rechargeable energy systems by chemistry [87]. Further research did not find any implementations of these documents.

In 2010, the Battery Association of Japan (BAJ), developed a labeling standard for lithium ion batteries. Near the three-arrow recycling symbol (blue for lithium ion), two numbers are printed. The first number (0-4) represent the "maximum amount of metal contained in the positive electrode" (0-Cobalt, 1-Manganese, 2-Nickel, 3-Iron). The second number (0-2) represent "metals which hinder the recycling of main metals" (0-none, 1-Tin, 2-Phosphorous) [88]. These are the only implemented labels fount in the literature research.

The General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ), and the ISO member the Standardization Administration

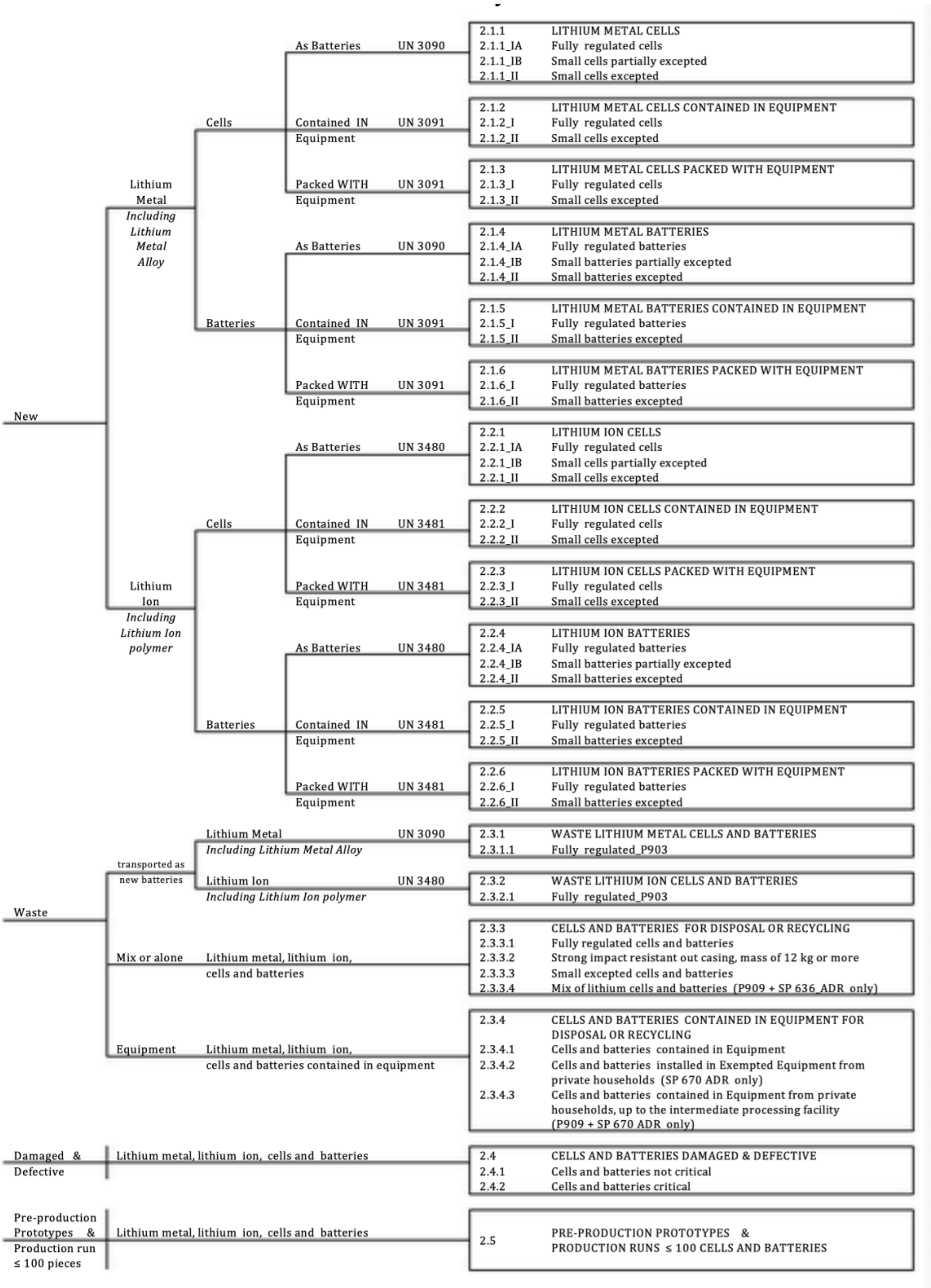

Figure 28: List of shipping modes regulated in the ADR19 [22]

of the People's Republic of China (SAC) developed coding regulations for electric vehicle batteries in 2018 [25]. The coding is structured in two parts; design information and production information.

The design information part information on the following, as illustrated in figure 4:

- Manufacturer (including production manufacturer, cascade utilization manufacturer and importer)
- Product type (pack, module or cell)
- Battery type (chemistry)
- Specification (defined by the producer)
- Traceability (defined by the producer)

and the production part provides information on the following, as illustrated in figure 5:

- Manufacturing date (year, month, day)
- Serial number (set by producer)
- Cascade utilisation (if second use).

In total there are 26 numbers and letter, which have to be carried in either a 128 linear bar code (complying with GB/T 18347 and GB/T 15425) or a QR code (complying with GB/T 18284 and ISO/IEC 16022 respectively) [25].

Code structure 1

Basic structure	Extended structure 1	Meaning
X1 X2 X3 X4 X5 X6 X7	X8 X9 X10 X11 X12 X13 X14	
X1 X2 X3		Manufacturer code
X4		Product type code
X5		Battery type code
X6 X7		Specification code
	X8 X9 X10 X11 X12 X13 X14	Traceability information code

Table 4: Part 1 of the code Chinese code structure concerning the design of traction batteries, copied from [25]

RSQ: How does the lack of detailed standard labeling in Europe affect the recycling schemes? Are there any European standards on the horizon?

RSQ: How is the Chinese code regulations adopted in Europe?

Code structure 2

Basic structure	Extended structure 2	Meaning
X15 X16 X17 X18 X19 X20 X21 X22 X23 X24	X25 X26	
Manufacturing date code		Manufacturing date code
X18 X19 X20 X21 X22 X23 X24		Serial number
	X25 X26	Cascade utilization code

Table 5: Part 2 of the code Chinese code structure concerning the production of traction batteries, copied from [25]

ELV directive

The end-of-life vehicle (ELV) directive 2000/53/EC was developed to "minimise the impact of end-of life vehicles on the environment, thus contributing to the protection, preservation and improvement of the quality of the environment and energy conservation, and, second, to ensure the smooth operation of the internal market and avoid distortions of competition in the Community"[89]. Basically, the ELV directive put the responsibility of the collection and EOL treatment of vehicles on the automotive OEMs. Guidelines on dismantling, storing and handling of traction batteries, assumed to be lead-acid and not li-ion batteries [89, 39]. Chapter 3.7 goes through the result of the directive, and the whereabouts of ELVs.

In Sweden, the automotive OEM has placed the producer responsibility for ELV treatment on Bilretur, which is owned by SBR and Stena Recycling, at 49% and 51% respectively. However, the EVBs are left outside of this responsibility structure, and the disposal responsibility is still left to the automotive OEMs [90].

RSQ: Is there any update of the ELV directive on the horizon?

3.9 European recyclers of lithium ion batteries

Europe has a number of already established LIB recycling plants, adding up to a current recycling capacity of 40,000 tonnes annually [26]. However, trying to confirm these numbers was difficult. Most numbers numbers come from literature that reference to outdated interviews. Below is a list of the European recyclers 14 are operational and 10 are planned. The 14

European Lithium Ion Battery Recyclers

State	Company	City	Country	Capacity (tonnes/year)	Process
Operative	Redux	Bremerhaven	Germany	10000	Mechanical
Operative	Umicore	Hoboken	Belgium	7000	Pyro, Hydro
Operative	Batrec (Veolia)	Wimmis	Switzerland	3000	Hydro, Pyro, mechanical
Operative	Eurodieuze Industrie	Dieuze	France	3000	Hydro, Mechanical
Operative	SNAM	Viviez	France	3000	Hydro, Mechanical
Operative	Duesenfeld	Wendeburg	Germany	3000	Mechanical
Operative	SungEel	Budapest	Hungary	3000	Mechanical
Operative	Accurec	Krefeld	Germany	2000	Pyro, Mechanical
Operative	Akkuser	Nivala	Finland	1500	Mechanical
Operative	Volkswagen	Salzgitter	Germany	1200	Hydro, Mechanical
Operative	TES-Amm (Recupyl)	Grenoble	France	1000	Mechanical
Operative	Nickelhütte	Aue	Germany	1000	Hydro, Pyro, mechanical
Operative	Van Peperzeel	Amsterdam	Netherlands	1000	Mechanical
Operative	Fortum	Harjavalta	Finland	1000	Hydro, Mechanical
Planned	Valdi Eramet		France		
Planned	Norsk Hydro		Norway		
Planned	Urecycle		Finland, UK, Netherlands		
Planned	Critical Metals		Sweden		
Planned	Northvolt		Sweden		Hydro, Mechanical
Planned	Bruce Metals	Sheffield	United Kingdom		
Planned	Greenhouse		United Kingdom		
Planned	Neometals		Germany		
Planned	Finish Minerals Group		Finland		
Planned	Stena Recycling		Sweden		

Table 6: Operational and planned recycling plants in Europe. Adopted from [26] and developed from own research.

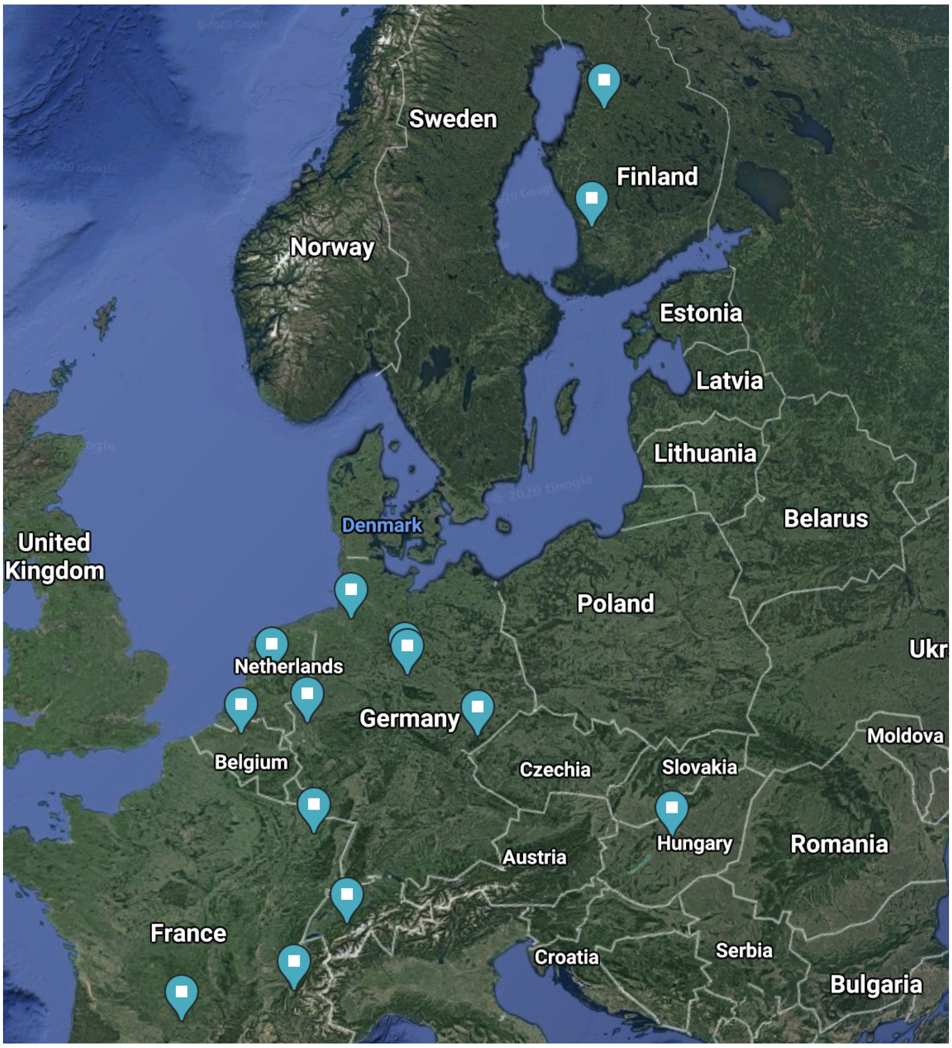

Figure 29: Locations of operational and planned recycling plants in Europe at the time of writing.

4 Findings and Analysis

In this chapter, the empirical findings are presented together with the Research Sub Questions gathered in chapter 3. Some RSQs are gathered into one larger question. The analysis of the findings are presented mostly as illustrations.

4.1 Empirical Findings

This chapter presents the empirical findings. Each RSQ is posed and answered in the order they appeared in the frame of reference, chapter 3. Some RSQs overlapped and have therefore been merged. As the RSQs and the industry experts both were classified with area and event tags, and then matched, each RSQ was answered by relevant industry experts.

Answering the RSQs

Which type of chemistries will be dominant in the return flow? Why is there a discrepancy between new projections on the return flow saying LCO and LFP will be dominant, while the demand in 2000-2014 was dominated by LCO and NMC?

Candidate W; the reason for the discrepancy is partially due to a reclassification of nickel-based portable batteries, from NCA to NMC and partially due to ”available for recycling” also include batteries available for recycling but that were sold to second life. Early batteries from Renault, Volvo, Nissan and General Motors contained NMC, but these are sometimes classified as LMO.

How are the thermal/chemical/electrical risks managed during storage and transportation of EOL EVBs? Where are the battery consolidation points located? How do they look like?

Candidate B; the police are often the first-responders as they are out on patrol. The fire fighters arrive later as they drive from the station. In a survey, 91% of fire fighters had no education about hydrogen or methane gas, and how to deal with these in an emergency. This number is probably similar for lithium ion batteries. Firefighters are only protected against hydroflouric acid (released during thermal runaway) for 10 minutes as the acid penetrates the PPE. Furthermore, electric vehicle batteries have been observed to reach thermal runaway three weeks after an accident. Responsible dismantlers and workshops should have a proper quarantine zone. A proper size of the quarantine zone should be 300 sqm per EVB. Furthermore, to illustrate the potential risks, circa 60 EVs burn every year in Norway.

Candidate C; there are no national or international regulations for how to store lithium ion batteries, but all storage regulations are set by the municipality. Candidate C says that after an accident, an unofficial rule requires damaged EVs to be three weeks in quarantine. This rule is often overlooked.

Candidate D; most electric vehicle batteries are stored in the vehicle outside until the battery is ready for disassembly. The batteries are directly after extraction disassembled into modules. The modules are then stored until dispatch on pallets with pallet collars in containers. The containers are situated ca 100 m from the main building, i.e. the fire prevention is passive. No real-time surveillance is practiced. No clear regulations to follow and the candidate says “we are in the dark”.

Candidate F; we store "yellow" batteries (there are many definitions), outside in containers with smoke, gas and temperature sensors. We store "green" (safe) batteries inside with thermal control and various warning systems. BEV batteries are stored on pallets in containers that have wooden lining, to minimize condensation.

Candidate H; the insurance cost for storing BEVs is included in the annual fee of ca 2,000 EUR for storing dangerous goods.

Candidate P; there are no explicit storage regulations for lithium ion batteries. However, usually the local fire and environmental authorities have supervision and grant storage approval. In Germany for example, different cities may have different storage regulations. There is an expressed frustration in the industry and the candidate believes Germany (and other countries) is working on a unified national legislation. The insurance companies have a lot of vested interest in these legislations because they continuously value and conduct risk assessments about how much and what they are willing to insure.

Candidate V; today, we do not disassemble or try to repair the battery but place the EV batteries on EUR pallets in containers in the backyard for storage. There is no surveillance such as temperature measuring. This storage can last circa one year. There is almost no communication between the dismantlers and the OEM, which is the reason for the long storage periods of up to a year and longer. The producer responsibility is inefficient.

Which actor is responsible for which part of the return flow today?

Candidate A; where the battery goes after end of first life is up to the owner. Today, for natural reasons OEMs have better collaboration with workshops than with dismantlers. Because the safety education has come further in workshops, most batteries are extracted there. From the workshops, most batteries are sent back to the OEMs for evaluation and research. Candidate A believes, however, that as EVs increasingly will reach a natural EOL (e.g. low SOH), in contrary to unnatural EOL (e.g. accident, failure) more will end up at the dismantlers. As the vehicles have become more advanced, as must the dismantlers. The candidate foresees a future in which the small dismantlers have been knocked out by larger, more advanced and OEM-backed dismantlers. Recycling is entering the fine rooms. Candidate A hopes that the OEMs and the dismantlers approach each other for closer collaboration.

Candidate C; electric vehicles have historically been very expensive vehicles. Sending an EV for recycling is the last resort. Most therefore go to workshops to be repaired. The insurance company have an obligation to restore the vehicle to the state right before the accident. This might sometimes induce changing the battery to one with similar SOH. After an accident, the insurance company tries to steer the vehicle to the closest certified workshop.

Candidate D; 60-70% of all vehicles at a dismantler comes from insurance companies. In practice, there are only two dismantlers in Sweden that can handle and dismantle EVBs, one of which is heavily backed by an OEM. The extractor is responsible for storage, transportation, handling, SOS and RUL analysis and dismantling. However, the RUL analysis is not done today and the SOS is notmuch more than qualified guessing based on experience. The dismantler usually disassemble the EVB to its modules because it is safer and easier to transport. The packs are simply too large, too heavy and contain too much energy to transport. There are few logistical solutions today that would allow a large return flow of EVs today.

Candidate E; ELVs are directed to authorized treatment facilities (ATFs), from which the

OEM can retrieve the battery or pay the ATF for further disposal. Pre-ELV battery swaps (battery extracted before the vehicle has reached EOL) institutes that a registered workshop must take care of safe storage, transportation and recycling. Hence, the private owner (end-user) is not involved in the collection or disposal of EVBs. There are incentives for OEMs to retake their batteries to put them to second use, or to do research to learn more from spent batteries.

Candidate F; the EVBs are extracted at the OEM repair workshops, collector workshop and dismantlers. We have a repair workshop where we repair batteries for some OEMs. Producer responsibility is problematic when it comes to second use. This has been resolved in contracts with very few players. We build something ourselves as you can see but it is primarily for our own projects. We build because we can and it is both profitable and environmentally friendly. At the same time, more of our owners and members want us to do it. Reuse is good in many ways, but I am somewhat skeptical when you see what some people remanufacture without traceability and with unclear disposal responsibilities.

Candidate L; the question of ownership may be the most important influence of the return flow. Increased transport as a service (TaaS) gives more ownership to the leasing companies and OEM. This may lead to better return flows, perhaps controlled by the OEMs.

Candidate O; when a BEV is in an accident, it becomes an insurance issue. The insurance makes sure the BEV is taken to a workshop, which analyze and diagnose the vehicle and the battery. If it is irreparable, the insurance company compensate the owner without taking over the ownership and sells it to the dismantlers, which handles the dismantling and send the vehicle carcass to recyclers. As vehicles become more advanced, as must the dismantlers. In 2010 there were 460 registered dismantlers in Sweden and in 2018 there were 290. Each dismantler must be able to process more vehicles and few can keep up with the rate of development.

Candidate H; there are online platforms that acts as marketplaces with bidding for wrecked vehicles. These ensure fair market prices, which attracts the insurance companies. Yet, however, there are too few BEVs returning and too few dismantlers that can receive them, resulting in BEVs not, or very rarely, being traded on these platforms.

Candidate P explains that there are three EVB flows that concern automotive OEMs today. The primary flow is when a battery pack and a vehicle are manufactured at different sites and the battery pack is transported to vehicle assembly. Batteries in the primary flow are usually packed in battery specific metal frames that go round-trip between the two facilities. The secondary flow is when an OEM manufacture a vehicle in country A, disassembles the vehicle and ships it to country B to avoid import tax and align with trade politics. This is called completely knocked down (CKD) transportation. The tertiary flow is the aftermarket transportation when an EV battery needs to be replaced. One new (or remanufactured) battery is transported from the OEMs storage to the workshop, and the faulty battery is packed in the same packaging and returned to the OEM. If the battery is damaged, a fire-resistant blanket is placed around the battery. Many batteries are being transported in the tertiary flow already today and they are transported in battery-specific boxes made of plywood or metal, with blocks that match the battery's fixation points or strapping to fixate battery.

Candidate S explains, we salvage crash-damaged electric cars to repair shops where we have ensured that the workshop has training in and resources to handle electric cars. Today it is mainly the branded workshops that can handle electric cars in a correct way. We repair more cars than we scrap so the repair flow is greater. 80% -90% of all crashed cars are repaired. In the event of total damage to electric cars, we salvage the electric cars to dismantlers who are trained in taking care of totally damaged electric cars. We never go in as the owner when repairing a damaged car. Only when the car is to be scrapped, we have agreed according to the insurance terms that we can sell the scrap to a car dismantler, thus we do not take ownership of the car. The training is mostly courses that the automotive OEMs and general agents themselves have. There is also general training in how to handle a crashed electric car when it arrives at the workshop. The candidate continues, we are not involved at all in the case of a natural EOL, but it is a producer responsibility that takes effect and then it is the general agent who is responsible to take care of the ELV. We previously had an insurance product for car manufacturers that we tried to launch where we as an insurance company would take care of ELVs, but there was a cool interest from the car manufacturers so that product has been phased out.

Candidate V; the return flow for electric vehicles, even if the vehicle is totally crashed, always goes through the workshops. The only exception might be if the EV is totally burned down.

Who owns the EVB in the different stages in the return flow, and where does the ownership change?

Candidate C; the owner of the battery depends on the brand and the type of vehicle ownership. If the vehicle is leased or pooled, the transport as a service (TaaS) provider owns the vehicle including the battery. If the EV is bought by a private individual, that person owns the battery. The only exception is Renault, which in many cases only lease out the battery to bring down the cost of ownership. It becomes a tricky problem with ownership after an accident. Instead of full compensation for the damaged car, the owner can occasionally (depending on insurance) accept circa 65% of the compensation and keep the vehicle. In this way, private people can keep the battery, making entry to return flow more difficult. Furthermore, there is collaboration between the collectors (El-kretsen in Sweden) and the insurance companies and between the workshops and dismantlers there usually are partnerships. To further elaborate on the topic, there are three major types of car insurance, non of which have anything to do with the warranty provided by the OEM:

- Motor third party liability insurance, which protects third party in case of accident (mandatory)
- Motor vehicle damage insurance, which protects first person's car in case of sudden unforeseeable external damage by using the vehicle.
- Insurance covering material damage, which protects the first person in case of theft, fire or similar.

Candidate D; the dismantler buys the EV and thereby the EVB. After dismantling, the modules are sold online much cheaper than other seller to get rid of them as soon as possible. The buyers are usually hobbyists or remanufacturers for second life. For the future, the candidate hopes for a more transparent aftermarket that can set market price on the modules.

Candidate F; volumes from dismantlers are small, but we work closely with the dismantler network. We have contract with OEM manufacturers as well as importers. There is a marketplace, but this is only second use in similar vehicles. We work closely with the insurance companies, too. Whether an EVB is reused or recycled depends entirely on the condition of the battery but an average is that around 40% of the disassembled modules can be reused. "Keep in mind that essentially the batteries we get in today are from cars that are not outdated and ELV".

Candidate I; there are three return flows that concerns the automotive OEM:

- If the EV battery reaches end of first life (EOfL) within the warranty period, the OEM has full control of the return flow. The battery is extracted by a contracted workshop and sent either back to the OEM for repair or remanufacturing if it can be repaired, or to recycling. The OEM has takeback function and keeps control. As the volumes increase, and cells are aged differently inside each pack, the opportunity increases for rearranging different EOfL batteries into second-use batteries. This has proven functional for many other complex spare parts.
- If the EOfL is outside the warranty (8-10+ years), the entire replacement cost is on the end-user (or the insurance company). The battery will probably be too expensive to buy new (ca 70% value of the vehicle). The OEM will therefore provide the option to hand in the old EV battery and buy a refurbished one (min. 90% SOH) at a discount. In this way, the OEM can keep control of the return flow.
- If the EV battery reaches EOfL due to accident, it becomes an insurance issue and the OEM loses control. A leakage point for the OEMs.

Candidate O; the battery OEM's plan to get all batteries back from automotive OEMs is dependent on the automotive OEMs actually owning the batteries, which is not the case for all privately-owned vehicles. Most vehicles are initially indirectly owned by the OEMs via financial institutions and are leased out or pooled. The consequence, however, is a higher turnover of vehicles. When leasing a vehicle, one expects a certain level of functionality. Most vehicles are therefore sold to private owners after ca 3 years of leasing. Almost all ELVs are therefore privately owned.

Candidate S; some OEMs, such as for Renault, lease out the vehicle and keep ownership of the battery. Otherwise, when we redeem a car, it is the dismantler who buys the scrap /leftovers from us and then they own the battery. When it comes to a battery that has lost capacity, it may be that the car owner tries to get money for the old battery, but we are not there yet.

Candidate U; most returning EVs are hybrids or plugin hybrids. If the vehicle is within warranty, as almost all are, a new battery is received from the OEM that is inserted back into the vehicle. The old battery is placed in the packaging that the new battery came in and is returned to the OEM. Electric vehicle batteries are not stored on site, yet. Our workshops today are not doing any work on the batteries but are only trained in reading data from the vehicle and extract the battery. There is only one dismantler or workshop in Sweden that remanufacture and repair electric vehicle batteries. Furthermore, in this day and age, time is of the essence. The workshop customers require to have their vehicles repaired quickly and locally. Most probably, the workshops must sooner or later be able to extract, analyze, repair and change EV batteries on site. The workshops do not own the EVs, and therefore are their flows for EV batteries almost exclusively to the OEMs. The dismantlers on the other hand owns the EV batteries and have more options. Some are sent for second use, some to second life and some to recycling. The dismantlers send the battery to where they earn the most, but if they do not want to carry the cost, they call the OEMs to enforce the producer responsibility.

Will the vehicle owner get reimbursed in the future when selling the vehicle to a car dismantler/remanufacturer?

Candidate A; the battery owner decides where the battery goes, which depends on its value.

Candidate E; the candidate sees a possible option where the waste management for EVBs are similar to that of cans and PET bottles. A pawn is placed on the battery, which is included in the initial purchase and is then returned to the customer when the battery is returned. Another method, which the automotive OEMs promote and is common for mobile phones, is that when a battery is returned, the customer gets a reduced price on the next purchase.

Candidate N; the recycling industry in China has developed so far that the recycling plants must pay for receiving batteries. It is another focus on raw material procurement there compared to Europe, while the cost of recycling also is lower.

Candidate P; recycler are mostly interested in NMC batteries because they have valuable material. LFP, on the other hand contain little valuable material. Here is a dilemma, less expensive material (LFP, NMC811 etc) is good because it leads to more batteries in our society, however it removes much of the incentives for recycling. The recycling cost must therefore be placed on the battery to be paid for by the end user, or the producer responsibility must be better enforced.

According to the Battery Directive, the producers (automotive OEM) is responsible for the disposal of the batteries, how does this show? The OEM has producer responsibility for the battery disposal but does not own the battery anymore. How does the OEM take responsibility for the disposal?

Candidate A; there are two different producer responsibilities, one for the vehicle and one for the battery. The high numbers of vehicles with unknown whereabouts is a result of inadequate surveillance. The are no requirements for the OEMs to actually collect ELVs. According to the legislation, the car producers must provide possibilities for proper disposal, through setting up a collection network with a certain coverage, make sure that the car is designed for 95% recyclability, and that the cars that enter the car manufacturers network of dismantlers actually are recycled to a minimum rate of 95%. In Sweden, the producer responsibility for batteries is regulated under SFS 2008:834. This regulation stipulates a target of 95% collection of industrial batteries, and 50% of the average weight. Notably, this target is not placed on the producers. Industrial batteries include all batteries "designed exclusively for industrial or other professional use or used in electric vehicles" [91].

Candidate F; automotive OEMs finances the entire system with an economic model that we have developed together. The vast majority of recyclers in Europe currently have gate fees but that is history within a few years.

Candidate G; the producer responsibility for batteries is always active and is regulated according to the "polluter pays principle". However, practically it can be enforced in different ways. When the owner doesn't want to carry the cost of the battery (does not profit on selling the battery), the battery owner usually contacts the collector. The collector enters into negotiations with the OEM about how they should provide or pay for disposal. Consequently, the collector's premier role is to enforce producer responsibility when needed. As they are none-profit, the candidate hopes for a secondhand market that is clever enough to make the collectors redundant, i.e the cost structures should be set up in such a way that the value is high enough to ensure disposal incentives all the way to recycling, or that the PR is acted out automatically. For batteries, the OEMs can choose to arrange their own collection system or connect to an existing system. Collection systems are most often used because they are more cost-effective (economies of scale, etc.), as many producers use the same system. In both cases, the producer is responsible for the costs. For batteries, the collection system does not need to have a specific permission - as it does for electronics. However, specific permits are always needed to run activities that handle hazardous waste. Traditionally, for portable batteries, the collector has a member fee and a disposal fee. Both of which are payed in advance. However, due to their long lifetimes, for industrial batteries (including EVBs), only the member fee is payed in advance while the disposal fee is payed at the time of the disposal.

Candidate I; automotive OEMs have traditionally contracted local dealerships and scrapyards to provide the possibility of proper disposal. However, the producer responsibility has not obliged the OEMs to collect vehicles to make sure they actually end up in a proper return flow. After 15-20 years, the vehicles are neglected by the OEMs. OEMs have good data on their aftermarket affairs and the older the vehicle the further east (in Europe) the spare parts are sent.

Candidate K; the OEMs have incentives to prioritize recycling over remanufacturing because they can not control what is happening in second life. They also rather want a few large recyclers than many small ones to minimize number of contracts. This is the case for battery collectors mostly but true for OEM as well. Furthermore, recyclers are popping up everywhere but current capacity is too low to handle all the lithium recycling needs. Intermediary storage is therefore needed. The dismantling/discharging and recycling costs are covered with gate fees, which are being lowered as the cost of recycling is decreasing. However, there is a short term fee increase due to capacity issues. However everyone expect the fee to decrease and potentially disappear.

Candidate V; from our facilities, there is no flow to recyclers or remanufacturers today. Still we have only received a handful of EVs. We want to make sure there is a serious buyer that can ensure a sustainable disposal.

Which part is responsible for the certified battery analyst to check the SOS and RUL of the battery? How is it done in practice? Are there any promising methods on the horizon that accurately can analyse the SOS and RUL of large battery systems? When are they commercially available?

Candidate D; much information can be extracted from the EVs own monitoring systems.

Candidate F; the SOS and RUL analysis is done in two phases and carried out by the collector (in this case the extractor). Before transporting to us, an assessment is made of the condition of the battery to define the condition. Almost all EV's internal system can provide some kind of information about the health of the battery and it is extracted regularly. We can do this via remote control or that the workshop takes out a diagnosis from the car that is uploaded to our portal. Based on historical data and experiences, we can then make an assessment. "I can not share how we calculate RUL.

Candidate I; the OEM performs the diagnostics of the battery at their partner dismantler or workshop. Sometimes however it is a thrid-party analytics company.

Candidate Q; in general, it is the same algorithms in the background for measuring state of safety (SOS) and remaining useful life (RUL) but used differently to attain different information. There are methods where an entire fleet send battery data through-air during usage. There are different tracking frequencies from vehicles to the OEMs, depending on brand, country and whether the vehicle is driving, standing still or parked. Our company needs 10Hz data points to do our analysis. This results in huge data sets, which are trimmed down to certain KPIs used in models. They don't need to save all of the time series. Some Asian customers (car fleets) have even higher data frequencies. Some in real time, some other save it on the vehicle and the send to the cloud. Some modelling can be done based on data from the vehicles. firstly, this data is sent to manufacturers, making it hard to attain. Secondly, the data are only discrete data points from more or less random driving, making it difficult to calculate RUL. There is always a risk of sudden drops of SOH in second life. The decay depends on how the battery is treated. There are however companies that claim they can predict a thermal runaway two weeks in advance by analyzing OCV.

Are there packaging solutions specifically designed for large EVBs? Or must the EVB be disassembled before transportation?

Candidate F; all batteries must be packed in accordance with ADR regulations, which defines which type of packaging to use. We have also developed several own boxes that are often used to have something to offer the market. We primarily send modules. The reason for this is the logistics advantage, but perhaps most importantly security. There are many things you do not see on a battery until you have removed the lid and can make visual assessments

Candidate G; the biggest problem with recycling is the transportation today. Packages for "red" batteries cost ca 200k SEK (ca 20k).

Candidate P; we have designed EVB specific packaging solutions for certain OEMs that allows transportation of entire pack.

From where will extraction, handling and storage safety regulations come and when?

Candidate A; there is no general safety education for handling EVBs, but each OEM has their own courses. For a dismantler and workshop, this means that they must send every worker to each brand's respective course all of which are basically the same. This is costly, yet necessary in order to gain the right knowledge today. A centralized system of safety courses is important for large scale handling in the future. Swedish Work Environment Authority (Arbetsmiljöverket) are responsible for the regulations concerning handling of high voltage systems.

Candidate C explains, all brands today have their own certificates for electric safety, all of which are similar but have different names. This multitude of certificates results in the workshops having to get one certificate per brand. This is inefficient and expensive.

Candidate T; mostly it is the OEMs that push the requirements for handling EV batteries. Our workshops are brand-specific because the OEMs have different workflows and procedures. This enforce the idea that the relation between workshops and OEMs will be increasingly stronger.

Candidate U; the workshops and dismantlers will make sure to have the required education and certificates. Today, all OEMs have their own battery educations, but the candidate anticipates centralized universal training.

Is there a trend towards more transportation by train, as it is more sustainable?

Candidate J; non-polluting transporting is always to prefer. The benefits of transporting black mass rather than packs, however, outweigh the benefits of transporting by train. Therefore, when developing a pretreatment plant, proximity to railway is more of a nice-to-have than a must-have.

Candidate N; the northern part of Sweden exports more products than it imports resulting in many trains travelling north with low fill rates. Production hotspots are probably common around Europe meaning these low fill rates are common. It may be smart to place recycling plants at these hotspots since many trains go there with remaining packaging capacity.

Packaging for transportation is dependent on a number from the list of waste. How is black mass classified with a UN number? Must this be done for every batch?

Candidate P says, it is probably quite difficult to classify black mass and as it is dangerous goods it might not automatically be simpler to transport than battery packs.

Candidate R explains, when classifying black mass with a UN hazardous code, all material fractions must be stated as a span, from which the classification is done based on the worse scenario. For example, a mix of two hazardous components (A and B), where the concentration of A varies in the span of 30-60% and B 40-70%, the mix is classified as 60% A and 70% B to avoid having to classify the mix more than once.

How long does it take to discharge battery to 0% SOC?

Candidate J; the discharge time is dependent on the SOC and the type of discharge method. Electric discharge can empty a fully charge battery pack in ca 4 hours, while solution discharge today take 24 hours. The solution discharge time includes several hours of redundancy to guarantee the batteries are emptied. This extra time will probably go down when we have more experience and data. Both methods has one problem in common, namely the rebound effect. When a battery is discharged to 0V, all lithium ions are forced over to the anode. There, every single ion being is not able to fully intercallate. When the discharge connection is broken, some small amount of ions travel back to the cathode recreating an open cell voltage (OCV). This voltage may be large enough to be harmful. To deal with the rebound effect we manually short circuit the connectors, this completely defuse the batteries.

Candidate F; we have developed various systems for discharge, which as of today are manual but automated after the summer. We have the capacity to unload about 100 packs at the same time. After discharge, we make a manual short circuit of the battery and have a marking system for it.

How much must the EVB be disassembled before crushing? How much is manual labor and how much can be automated? How well can the materials be separated at scale? How is the black mass quality and yield dependent on throughput and the homogeneity of the input? Can a pretreatment plants receive all types of electric vehicle batteries?

Candidate J; in theory, pretreatment plants can receive all types of electric vehicle batteries.

Some packs and modules are more difficult to pretreat than others. Most battery systems with cylindrical cells have significant amounts of adhesives (mechanical and heat conductive glues) making them more difficult to process than prismatic and pouch cells that are easier to pack without adhesives. Furthermore, not all chemistries are wanted. For example, if the black mass is going to material recovery used for NCA-cell production, the input to the pretreatment plant cannot accept LFP-cells because there must be no trace of iron. Furthermore, the yield of the material recovery is highly dependent on the pretreatment input. As the settings for the material recovery processes must be tuned based on the black mass composition, the narrower the composition the better yield. It is probably simpler to separate the materials into different fractions before crushing.

Candidate D; it is only the candidate that does the disassembly at the dismantler, and the candidate is self-taught. The extraction requires ca 50 sqm for a car lift and ca 50 sqm for the battery pack disassembly. The disassembly is done manually using adequately electrically insulated tools. Regarding the input to the pretreatment plants, the PHEV and HEV batteries are not worth much at all because of their low energy and power density as well as cheap materials. There is simply no demand for them. As Tesla was first on the market with energy and power dense BEVs, these batteries have the highest secondhand demand.

Candidate K; sorting is important but I would go as far as say it is the pre-requisite of large-scale recycling. Large scale recycling can be done with poor sorting but generally the rule of thumb is the less sorting of batteries the worse yields on recycling of materials you get. In other words, you can manage the recycling without sorting, but you will get lower than battery grade quality.

Candidate L; when it comes to transparency of information, car dismantling and recycling is a very slow-moving industry. No big difference between 15 years back and today. Digitization will probably take many years still. A reason for this lack of battery information (e.g. dismantling/disassembly guidelines) for external parties is protectionism of IP because of the lack of trust in a third-party info system. This makes automation of disassembly difficult.

What throughput does the crushers have? Analogously, how many crushers and shredders are needed in Europe to preprocess 100% of recycling-available LIBs?

Candidate J; the benchmark is 3 tonnes per hour for an industrial crusher.

Based on a rough estimation (30,000 tonnes per year)from figure 2 and assuming a crusher throughput of 3 tonnes per hour with 90 % up-time, the required number of crushers (N_c) in Europe by 2025 will probably not be more than a handful, see 1. Important to remember that the number of required throughput will increase exponentially as explained in chapter 1.2.

$$N_c = \frac{30,000 \text{ tonnes}}{3 \text{ tonnes/h} \cdot 8760 \text{ h} \cdot 90\% \text{ up-time}} = 1.3 \text{ crushers required in Europe in 2025} \qquad (1)$$

Can the electrolyte be recycled or reused? If not, how is it disposed of?

Candidate J; currently the evaporated electrolyte is collected by certified recyclers. Exactly how the electrolyte is recycled is unknown to us. We hope that the we can reuse the electrolyte in the future, but we are not there yet.

Are the processes energy intensive? How much should the electric energy mix be considered when placing a pretreatment plant?

Candidate J; compared to the material recovery processes and the cell production, pretreatment is not energy intensive. Nevertheless, a green energy mix is always to prefer. The pretreatment plants might recover the energy in the batteries, somewhat making the pretreatment plant grid-independent.

How will the lack of charging infrastructure influence the whereabouts of ELVs?

Candidate A; because of the lack of charging infrastructure, few EVs will be exported to East Europe or to Africa in the short term. This will create a larger secondhand market in Europe, which might lower the price of EVs, which in turn incentivises recycling. However, these countries might be quick to electrify. Perhaps they have charging infrastructures in place in time for the big surge of EOL EVs, and the risk for illegal export may remain.

How does the Basel Convention affect the transportation of EOL batteries within Europe?

Candidate E; when transporting a battery from country A to country D, all countries (A,B,C and D) must be informed about the shipment. Minimizing the number of borders, may simplify the transport.

How is the ambiguity between the different regulations affecting the return flow? When are electric vehicle batteries considered as waste?

Candidate A; the candidate hopes for a more regulated second market to prevent EVBs from ending up in the hands of hobbyists, to limit the risks of danger to both person, property and environment. Because of the early market, there is still room to become a large player in the aftermarket and in the return flow.

Candidate E; because the Battery Directive from 2006 did not specify LIBs, they automatically got included in "other batteries" and therefore never got a specific waste code. Together with the fact that LIBs have high potential of being used a second time, in the same application or in a new application, it is unclear when the LIB should be classified as waste. Today, the European List of Waste does not classify spent batteries as waste, however, Austria and some states in Germany have already done so. Spain decided that LIB should be considered as Amber list in the Basel Convention. After the pretreatment, the black mass can be considered as a product mix, product substance or waste.

According to "How to report on shipments of waste according to the Regulation 1013/2006/EC", the European member states are strongly urged to indicated whether the believe a certain waste is considered hazardous or not. Because of the lack of classification, there are some room for interpretation. It is therefore up to the European member states to define whether an EV battery should be considered hazardous or not [92].

Candidate G; the definition of a waste battery is it being broken and not intended to be fixed. Broken electronics are not allowed to be exported for reparation, with some few exceptions that requires extensive documentation. I assume that the same rules for batteries apply to electronics. We have not investigated this issue as it has not been relevant. A broken EV battery may have to be repaired in the country it is located in.

Candidate R; the classification of a battery as waste or product depends on where it is heading. All batteries that are going, or intended, to be disposed of are classified as waste according to the Swedish environmental code 1998:808. In the same environmental code, recycling is defined as the actions to prepare material for reuse, while material recovery is defined as the reprocess of waste to new material or products that are not going to be used as fuel or filling material [?]. Batteries that are transported for recycling are thus waste, while batteries that are transported to reuse or second use are products.

What penalties corresponds to illicit transportation of waste and dangerous goods?

Candidate P; penalties for smaller violations of transport regulations, even if no accident has occurred, are fines around 50k. In Germany, the person that signs the dispatch document is personally liable, where prison is part of the penalty scale. Therefore, many transport companies use certified boxes even when there are options to use non-certified. Modules for examples, even when being quite rigid, are generally recognized as too weak for being transported on a pallet.

Candidate R; the individual that packs and loads dangerous goods must be certified according to chapter 1.3 in the ADR. In Sweden, the punishment for illicit transportation of dangerous goods is regulated in the legislation for transportation of dangerous goods (SFS 2006:263). The individual risks fines and imprisonment up to two years.

How does the lack of detailed standard labelling in Europe affect the recycling schemes? Are there any European standards on the horizon?

Candidate F; we have our own system, but it should have been more centralized right from cradle to grave.

Candidate I; a central disassembly guideline such as IDIS should be further developed to include EV batteries too.

Candidate L; efficient and safe return flow is dependent on battery information. There is no universal and transparent transparent labeling that specifies exactly contents and technicalities of a battery today. Therefore, dismantlers are becoming increasingly more brand specific and collaborate closer with OEMs. On a similar note, when first responders look up information on a vehicle based on the number plate, the only information is "electric vehicle". It would be good to have information about how the battery's construction and how it is placed and fixated in the vehicle as well as all the chemistries. There are projects that aim to ensure a trusting data base to improve information transparency in circular economies. Step one is to provide a generic database to which actors can upload info and everyone can read that info. Step two may be to add levels of reading access, so that actors that need more specific information may have access to it without making that information public. IDIS is a great tool in theory but it lacks technical details required for safe battery dismantling. It may be used for a foundation for this new system.

Are there any updates on relevant directives on the horizon? How may increased high technology systems and thus traceability on modern vehicles decrease the number of VUWs and how do they go along with GDPR? How is the Chinese code regulations adopted in Europe?

Candidate E; the Battery Directive is currently being revised, and a pre-study to an update will be presented in October 2020. An enforced update of the directive is not expected before 2022. The update contains two major measures that concerns LIBs; "extended producer responsibility for the collection of industrial batteries" (henceforth called the EPR-measure) and "additional collection target for industrial batteries" (henceforth called the CT-measure). The EPR-measure states that the EPR for industrial batteries is not well defined currently. EPR for traction batteries is not even mentioned in the Battery Directive. All producer responsibility for the EV batteries today is voluntarily assumed by the OEMs. Nevertheless, it is understood that all OEMs do assume producer responsibility, and the costs are not put on the end-user. The ELV Directive does not place EPR to electric vehicles, and thus not to their batteries. The new directive will define EPR for EVBs. The EPR must be placed on the OEMs, and the end-user should not pay any costs (a pawn is nevertheless not excluded). Looking at "industrial batteries" is too wide because it includes too many types of batteries with varying hazardous levels, geometries and lifetimes. The CT-measure for EV traction batteries states that current directives implicitly sets a 100% collection-and-recycling target for EV batteries, since it is not allowed to dispose of the batteries in any way but recycling. It concludes that it is questionable, however, whether a collection target is feasible since crucial information is missing (see list below). Therefore, a new target should not be established, but explicitly expressing a 100% collection-and-recycling target.

It is questionable whether a collection target is feasible since following crucial information is missing:

- Amount of exported EVBs is unclear
  - Still insufficient systems to monitor and quantify ELV exports
  - Cannot be improved using RFID due to GDPR
- Waste batteries available for collection is unclear because of the arbitrary assumption of a 3-year lifetime, after which the battery is available for recycling. This is not true as most batteries have longer lifetimes.
- Cannot relate collection targets to POM numbers because the lifetimes of different type of EVBs varies a lot and are too long in relation to the market growth rate.

Candidate F; the Battery Directive is under revision and a new directive will probably be available by 2021/22.

Candidate M; the challenge with transparent traceability is to get all the producers willing to share their data. Yet, the aim is not to have one giant database but to develop how information is packaged so the required information can be exported when necessary. Usually the producers have all necessary information for efficient recycling. But in reality, when a recycler or collector receives thousands of products per day, they do not have the time to call up each producer and check the information. The key challenge is thus to develop a traceability system that can transfer that information efficiently to where it needs to go.

Candidate M; traceability is not practiced much today. When producers sell a product, they lose control over it and all data is inaccessible. It is very difficult to know where the product ends up. There are occasions when there is product return or repair within the warranty period that provides some oversight. Concerning electronics, there is always a producer responsibility connected to the products. In Sweden this producer responsibility is outsourced to Elkretsen which collects electronics and sort them into the correct return flows. In the future, candidate

M hopes for a common inter-industry viewpoint on how to track products. Battery traceability should not have one solution and electronics, food or clothes other solutions. Each industry should not reinvent the wheel for traceability. Today there are no standards, but the industries that have come the furthest are the fish and the pharmaceutical industries. Many people in the industry want to see a top-down implementation of a traceability system, from EU level. If top-down is the case, it is very important that the system actually suits the industry and creates value. Proactive players can, and should, influence the development.

Any adoption of the Chinese code regulation presented chapter 3.8 has not been identified.

Further empirical findings

Candidate L; the candidate has seen an example of an EV battery being stored charged in a wooden box inside at technical university. "If there would be an explosion at our university, we would know why. Even researchers studying li-ion batteries might not know how to properly handle them".

Candidate O; circular economy is very important. However, the problem with them are the difficulty to have a circular economy without many monopolies. Virgin material flows are good because they ensure a free market. When they are circular, the trends today point to companies ensuring their own benefits.

Candidate C; Covid-19 have forced people to lower their spending. Fewer people hand in their car for repair at workshops to avoid insurance excess costs, meaning that the dismantlers (providing spare parts) have lost many customers in recent months. Some have filed for bankruptcy. It shows how dependent dismantlers are on their business of selling spare parts.

Candidate T; The largest problem for a large Swedish car dealership (this does also apply to the OEMs) is the low margins on EVs. Its ever more difficult to make a profit. Also, as services are a large part of the workshop business (78% of operating profit), the fact that BEVs are less likely to need a repair, this business is vanishing. Nevertheless, BEVs wear out the tires quicker and do crash more often (both to some degree due to faster accelerations). Time is always at the essence for the new generation, which will be the owner for BEVs. Therefore, time consuming transportation between different actors will probably not be optimal. The candidate presumes that most of the analysis and dismantling will be done at the workshops.

Candidate F; traceability must be better regulated, emissions from the production of batteries and, of course, emissions from collection and recycling should be more strictly regulated. Furthermore, competence-requirements for those who will work on the batteries are something that must be prioritized. The largest share of emissions in the return flow occurs when the batteries are exported for recycling. This is an important factor we are now solving with the establishment of a new pretreatment plant in nationally. The biggest challenges today are gray zone sales and little traceability of batteries exported outside our system.

Candidate H agrees, today there are many illegitimate dismantlers that have no certification, have no respect for nature nor for correct documentation. The candidate therefore wishes for a more transparent playing field with stricter, but most of all, enforced regulations.

Candidate O; too cheap transportation and insufficient trade restrictions make it too easy to manufacture globally, leading to unsustainable supply chains.

Candidate I; transportation is very cheap today. This results in products being transported to where the processes are the cheapest. For EV batteries this means, if a battery reaches EOL (naturally or un-naturally) it may be transported across the world for proper disposal. This does not align with the environmental aspects of electric transportation. Candidate I continues, the most common reason for failure is the BMS and not the cells.

Candidate I; the OEMs EVB return strategy;

1. Repair/refurbish and return to new vehicle (reuse)
2. Remanufacture and use in new application ()
   (a) There are very few, if any, commercial solutions yet. The candidate states that EV batteries are designed specifically for EVs, all the way from the chemistry and cell level to the pack level. They might not always be suited for remanufacturing.
3. Recycling
   (a) The automotive-OEM rather would have one global recycler than many small ones. They also want the recycled battery material to return to their battery-OEM supplier.

Candidate I; because PHEVs also have a combustion engine, the state of health at EOL can be as low as 65%.

Candidate O; there are 7 million vehicles have unknown whereabouts in Europe today. It costs roughly 6 annually to keep a car deregistered (not in traffic, not yet scrapped) in Sweden today, while no debt below roughly 15 is collected. Thus, many vehicles are deregistered and kept in the "backyard" rather than sent for recycling. Since there are no follow-ups on deregistered vehicles, no one knows how many of them actually are still around. There should perhaps be a fine for those who cannot point at their vehicle. ICE vehicles usually become ELV after circa 17 years. Electric vehicles are relatively expensive today, meaning they have a long depreciation time. Moreover, modern EVs are mostly made of aluminum and composite materials that do not corrode and the electric motors are very durable compared to ICE vehicles. The EVBs have also proven to live longer than anyone could wish for. The lifetime of an EV is therefore expected to be 20-25+ years. Why this is not shown in the statistics is because almost all vehicles that return are faulty or have been in an accident and the volumes on the roads are small. The true natural lifetime of an average battery is yet to be discovered.

Candidate V; as the vehicles becomes increasingly advanced, I believe there will become fewer but larger dismantling sites. As a rule of thumb, Sweden needs ca 5 dismantlers per county (perhaps more in the north), thus ca 100. Furthermore, there are three certified recyclers for members of Bilretur. One of these are the majority shareholder of Bilretur. However, the minority owner, SBR, has the network of dismantler and can act like a union preventing monopole pricing.

4.2 Analysis

The empirical data from the interviews point indicate two return flows. The unnatural return flow being most common today, and the natural return flow that will be the most common in the future. In the following subsections, the two return flows are explained. In the appendix, the entire flows are illustrated in their entirety including comments.

Unnatural return flows

An EV battery enters the unnatural return flow due to a fault or an accident, and is the most common reason for reaching end-of-life today. The unnatural return flow is made up of three major routes, hereafter named:

1. The take-back flow
2. The delay flow
3. The semi-closed flow

The take-back flow The take-back flow, depicted in figure 30, outnumbers all the other flows today. It is entered after an accident or fault, while the EV is with warranty. Ultimately, the battery ends up at the car OEM, where it is researched or used in 2nd life pilot projects.

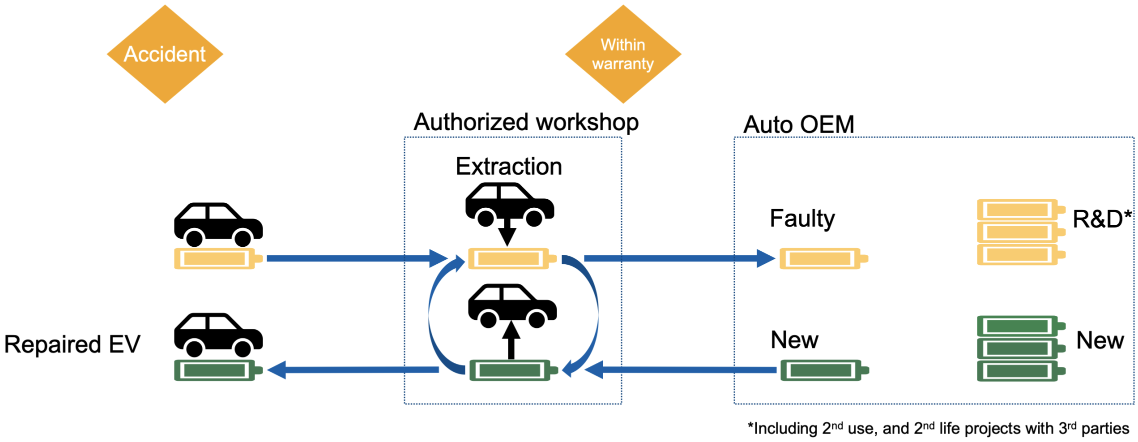

Figure 30: Own illustration of the take-back flow

The delay flow The delay flow, illustrated in figure 31, is the second most common return flow. It is entered after an accident that is too expensive to repair and the extractor lacks sufficient training and equipment and access customer (i.e. recyclers or remanufacturers). The battery ends up in unsurveilled storage at the car dismantler, usually on a pallet inside a shipping container, where it sometimes is stored for years. No external consolidation points were identified for any of the return flows, but all EVBs awaiting transport were kept locally at the extraction site.

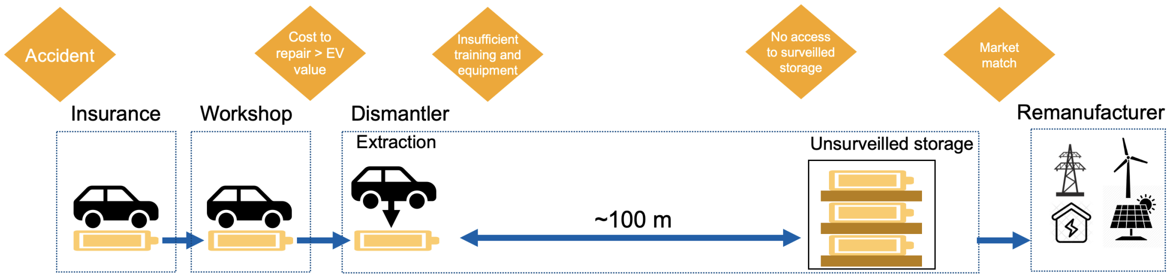

Figure 31: Own illustration of the delay flow

the semi-closed flow The semi-close flow, illustrated in figure 32, was only found at one place. As this specific collaboration between a dismantler and a collector is the market leader for end-of-life treatment, the semi-close flow is expected to be imitated and grow.

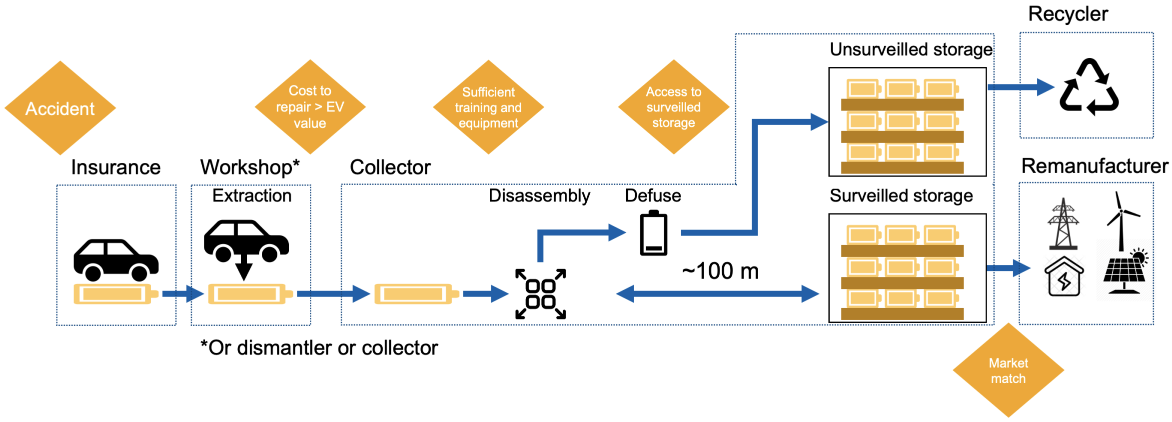

Figure 32: Own illustration of the "semi-closed flow".

Key takeaways from the unnatural return flow

- The take-back flow is the most common return flow today, leaving a majority of the EV batteries unavailable for recycling.
- Dismantlers must advance technologically to cope with the future increase of EV batteries. This will probably lead to a decrease in number of dismantlers.
- The consolidation points mentioned in chapter 3.5 under *Transportation* are all located at the extraction site.
- RUL assessments is still commercially undeveloped, despite many companies claiming they have the solution.
- The heritage of producer responsibility is ambiguous when selling an end-of-life electric vehicle battery, hindering expansion of second life applications.
- Extractors want expanded demand on end-of-life electric vehicle batteries, promoting an open secondary market.

Natural return flows

An EV battery enters the natural return flow due to low state of health, and will be the most common reason for reaching end-of-life in the future. The natural return flow is made up of two major routes, hereafter named:

1. the second-use flow
2. the end-of-life flow

the second-use flow The second-use flow, illustrated in figure 33, is entered when the EVB reaches a SOH limiting the driving experience expectations. To not waste an end-of-first-use battery, the car OEMs are developing take-back schemes. An end-of-first-use battery is refurbished and put back into a vehicle with suiting demands.

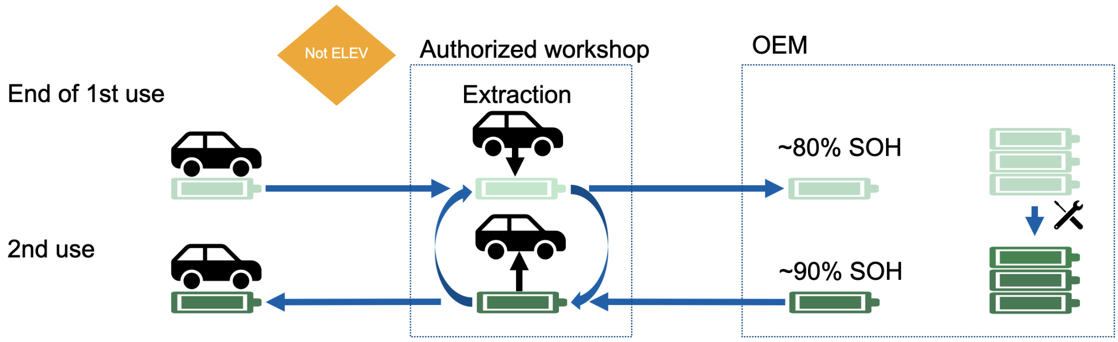

Figure 33: Own illustration of the "second use flow".

the end-of-life flow The end-of-life flow, illustrated in figure 34 is the final flow, which most EVBs will reach eventually. It is entered when an EV with an end-of-second-use battery (E2U) or end-of-life EV (ELEV) is taken to a car dismantler that can handle EVs. Today, there are many established online market platforms for spare parts, which might start trading EVBs. However, none of these markets have done so today.

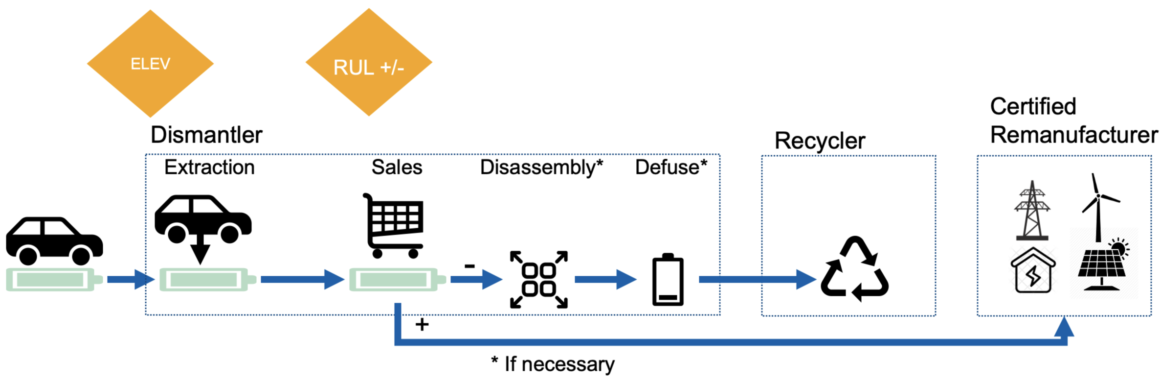

Figure 34: Own illustration of the "end of life flow".

Key takeaways from the natural return flow

- Auto OEM's take-back solutions will gather most end-of-first-use (E1U) batteries. This optimizes the use of the battery in the application it is designed for and allows the OEM to sell each battery twice
- The workshops' roll will probably remain the same as today
- The collectors' roll are yet to be decided. Some are already working hands-on with EVB EOL-treatment, while other will continue to focus on enforcing the producer responsibility whenever necessary
- Sourcing the right batteries for the recycling processes or second-life applications is crucial for scalability. A market platform or improved cross-industry collaboration, and stricter regulation are prerequisites for a circular battery economy.
- Determination of remaining useful life is crucial for optimal reuse or second-life of batteries

5 Discussion

In this chapter, the research questions are answered followed by a discussion about the limitations. The maps including the return flows in their whole are attached in the Appendix.

5.1 Answering RQ 1

RQ1: Which aspects influence the European logistics of end-of-life electric vehicle batteries transported for recycling today and how may these change in the near to mid-term future?

Many batteries will likely be used more than once or even twice and go through some kind of return flow in between. Therefore, it makes sense to talk about end-of-first-use (E1U), end-of-second-use (E2U) and then about end-of-final-use (EfU), where the EfU equals end-of-life (EOL). At end-of-life the battery enters the final return flow.

There are two main reasons for a battery to enter the final return flow; unnaturally or naturally reaching end-of-life. Today, the unnatural return flow is most common, however, when the number of EVs that reach end of life, the natural return flow will become the prominent one. Whether the battery is going to recycling or remanufacturing in the short term depends on the following key aspects:

- if the vehicle is with or without warranty
- if the cost to repair is higher or lower than EV value
- if the extractor has access to certified customers (recyclers or remanufacturers)
- if the extractor has sufficient high-voltage training and equipment
- if the extractor has access to surveilled storage

In the natural return flow, which will be the most prominent return flow in the near to mid-term future, these aspects will change to include the following two aspects, which determine whether the battery goes to second use or second life:

- If the vehicle has reached EfU
- If the remaining useful life (RUL) is enough for second use

5.2 Answering RQ 2

How do these aspects influence the strategical deployment of lithium ion pretreatment plants in Europe to facilitate efficient entry to recycling streams?

The empirical findings have produced a number of must-have and nice-to-have requirements to consider when building a pretreatment plant.

The pretreatment processes are quite developed and are mostly dependent on the input volume and homogeneity. The barriers are more business-related than tech-related. Meaning, the pretreatment plants are dependent on a large flow of the same type of batteries. To achieve that, there are some of key aspects to consider:

Must-haves when building a pretreatment plant

- Consolidation and sorting functions to allow running the pretreatment processes in batches to ensure a homogeneous input, alternatively access to a market for sourcing a homogeneous feed.
- To comply with local storage regulations there must be a close collaboration with fire department, municipality and other regulatory stakeholders. The storage for yellow and red batteries should be separated from the main buildings and have at least smoke, gas and temperature sensors.
- EVB-certified workers. These certificates are provided by each OEM respectively, until there is general training
- Discharge system that can handle the rebound effect at scale

Nice to have when building a pretreatment plant

- Short term, close proximity to EVB-certified workshop to claim the unrepairable batteries
- Long term, close proximity to car dismantlers or at a car dismantler as the storage and transportation are main constrains in the return flow. As shown in figure 35, there are possibilities for pretreatment plants to become intermediaries at the car dismantlers.
- Own car lift and extraction tools to allow entry of return flow at the pretreatment plant.
- Quarantine zone for critically damaged batteries, large enough for 300 sqm per battery and a three week accumulation.
- A traceability system that allows deregistration of EVBs, improving full life-cycle traceability.
- Access to railway transportation
- Few country borders between the pretreatment plant and the material recovery plant
- A green energy mix to align with environmental mission
- Be located in a manufacturing hot-spot to which trains and trucks already go with low filling rates.
- Collaboration with car OEM to get disassembly guidelines

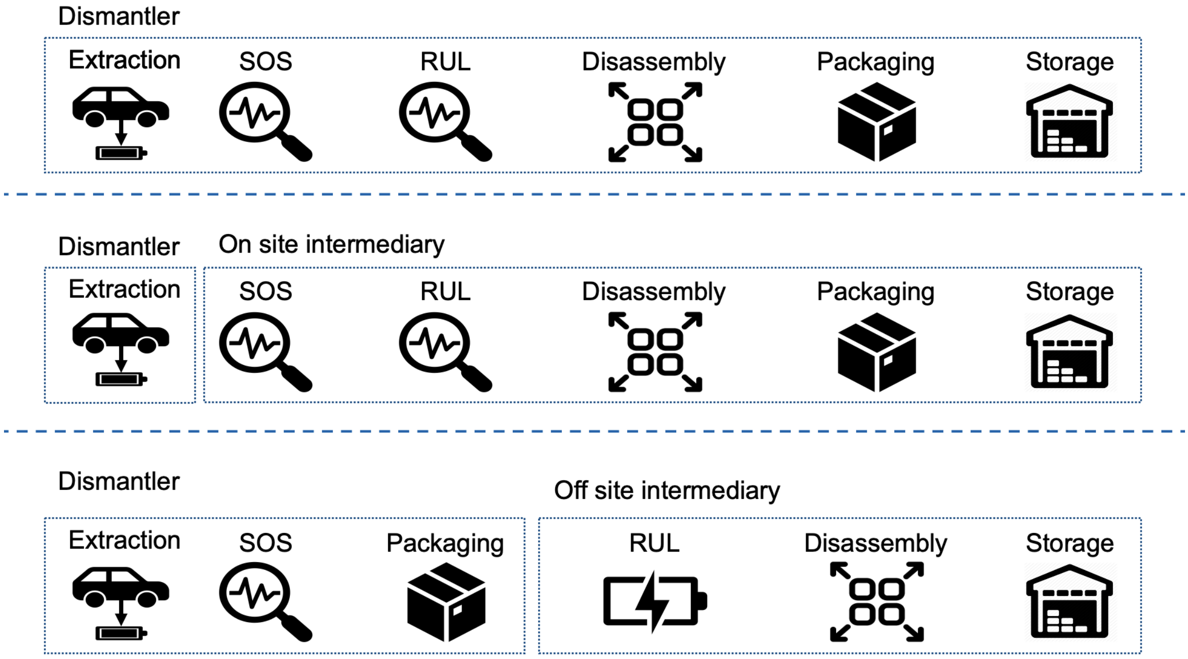

Figure 35: Own illustration of the possibility to become an intermediary at the car dismantler.

5.3 Uncertainty analysis

Throughout the research, multiple uncertainties in the data gatherings have been identified. They can be summarised as data-, speed- and bias-uncertainties. All of which are important to acknowledge, but do not challenge the validity of the results.

First of all, the data on how many, where and when EVs will reach end-of-life in the coming years is very limited. Because of the insufficient regulations (chapter 3.8), little effort has previously been allocated to collecting that data. This has made it difficult to pinpoint geographically where most batteries end up today. Furthermore, it is difficult to be sure about which chemistries are entering the return flow as there have been ambiguity in the classification. Therefore, pointing to where a pretreatment plant should be placed based on volumes and chemistries has not been manageable.

The second reason for the lack of data is the sheer speed at which the market and technology is developing. Still, the literature and the interviewees do not know how many years a battery lasts in general. Most EV models and brands have different cells, modules and packaging solutions as well as different driving behaviours, making it even more difficult to generalise the lifetime. This data may actually be known, but in an emerging market the IP is well protected and not publically accessible. As a consequence, the speed at which this research is outdated is prevalent. By talking to the market experts about the future, however, the time-span for the validity of the results has been maximised.

Finally, the third type of limitation is the fact that the data was collected through interviews. The different interviewees biases could be identified as some of the interviewees had almost contradictory experiences and thoughts, especially when it comes to the potential danger of LIBs. The industry lack consensus. Furthermore, in the interviews it proved to be difficult to correctly discuss aspects of the return flows based on the whether the EV was a hybrid, plug-in hybrid or pure electric. It should have been stated more clearly what type of EV the interviewee was discussing. Therefore, all types of EVBs were combined to general flows. On another note, a majority of the interviewees held executive positions giving them a good oversight, yet it excluded much of the hands-on experience important in understanding the real challenges with EVB handling. As the return flow is at an early stage, no "general truths" could be stated since every interviewee, too, were looking for answers.

6 Conclusions

In this chapter, the key outcomes are presented and how they contribute to current research. Lastly, suggestions on further research are proposed.

6.1 Key Outcomes

The study aimed at investigating the return flow of electric vehicle batteries after they reach end-of-life. By conducting interviews with 22 experts from different parts of the return flow, the study successfully mapped the return flow, as illustrated in the the analysis (chapter 4) and appendix.

The mapping was divided between the unnatural and natural return flow, where the former is more common today and the latter will become the main return flow when EVs reaching end-of-life continue to increase. Due to the complexity and many aspects the unnatural return flow was divided into three different paths and the natural into two. The aspects were then arranged into must-haves and nice-to-haves when strategically deploying a lithium ion pretreatment plant.

6.2 Contribution to Research

This study advances the small pool of literature on the highly relevant topic of return logistics of electric vehicle batteries. Efficient and large scale recycling is crucial for the transition to a circular society and dependent on understanding how the stream of end-of-life EV batteries looks like. Hopefully it emphasises the need to drastically improve the return logistics.

The extensive literature researched in the Frame of Reference (chapter 3) highlights many of the aspects of lithium ion batteries allowing this study to introduce anyone to much of what is needed to know about lithium ion batteries and their logistics. The key contribution is bringing together viewpoints from stakeholders in all areas of the return logistics and the current challenges in EVB recycling have been nuanced and detailed.

Furthermore, the study identified a number of challenges that bothers multiple actors. Also, it illuminated the limited consensus on important matters such as how to store, transport and trace EVBs across the return logistics. This insights generated many suggestions for further research.

6.3 Suggestions for Further Research

Recovering the critical raw materials stored in the millions of EVs reaching end-of-life in the coming years is crucial for sustainable electric mobility. The following areas need much more research, and can be summarised as regulation-, product- and business-development.

Regulation development Today, the life cycle traceability of vehicles is insufficient and little is known about when and where vehicles are exported and imported at end-of-life. Little is known of where they actually go and this insufficiency has resulted in 7 million vehicles having unknown whereabouts today. More research is needed to develop better regulations that ensure traceability. A logistical overview would also illuminate business opportunities and synergies across the vehicle ecosystem.

The currently limited producer responsibility is one reason for the lack of traceability and low scrap rates. When EVBs have the potential of being used multiple times with multiple actors, much effort is needed to clarify who is responsible for the disposal at end-of-final-use.

The dismantlers are forced to get training in EVB handling from each car OEM respectively, which is costly and ineffective. General training is needed be developed to scale up the efficiency in the return flow.

Product development Transportation is very costly today (if done correctly), much because of the strict regulations considering dangerous goods and waste. Developing an industry-wide standard packaging that can carry most types of EVB models would lower logistical costs drastically.

As mentioned in the limitations (section 5.3), there is no consensus for how dangerous LIBs actually are. In order to develop adequate regulations for LIB storage, much research is needed to further the understanding of thermal runaway and the toxic gases, as well as why and how these risks depend on bad handling, storage and transportation. This understanding must quickly be implemented to first-responders, whom today struggle to fight LIB-fires and to all actors that store EVBs that today can not confidently ensure safe handling. Also, further research is needed in finding the optimal extinguishing methods, as "a lot of water" resulting in toxic run-off water probably is not optimal.

Determining the RUL is very difficult and is not practiced in the return flow. The value and therefore the return flow of an EOL EVB will be based on the contained materials and the RUL. To optimally use the EVBs, RUL determination is needed to be further developed and then implemented and practiced at car dismantlers.

Business development To ensure that each battery is used optimally, better pricing modelling is needed. A secondary market with free bidding could decide where an EOL EVB should go. The market would automatically value the RUL, SOH, capacity, voltage, and internal resistance versus the raw material.

Recycled material is more expensive today. However, perhaps the car OEMs can sell their vehicles at a higher price if the material is supplied from a recycle-feed. Research is needed to understand how much more are end-customer is willing to pay for an electric vehicle with recycled battery-material.

Sharing economy and car pooling will probably increase. Research is needed to understand how non-private car ownership affects the return flow.

Many companies are starting to understand the value of recycling to secure their supply chain. This, however, risks that all battery manufacturers take back their own batteries, creating monopolistic circular flows. Research is needed to understand how circular monopoly can hinder the sustainable benefits usually assigned to circular economy.

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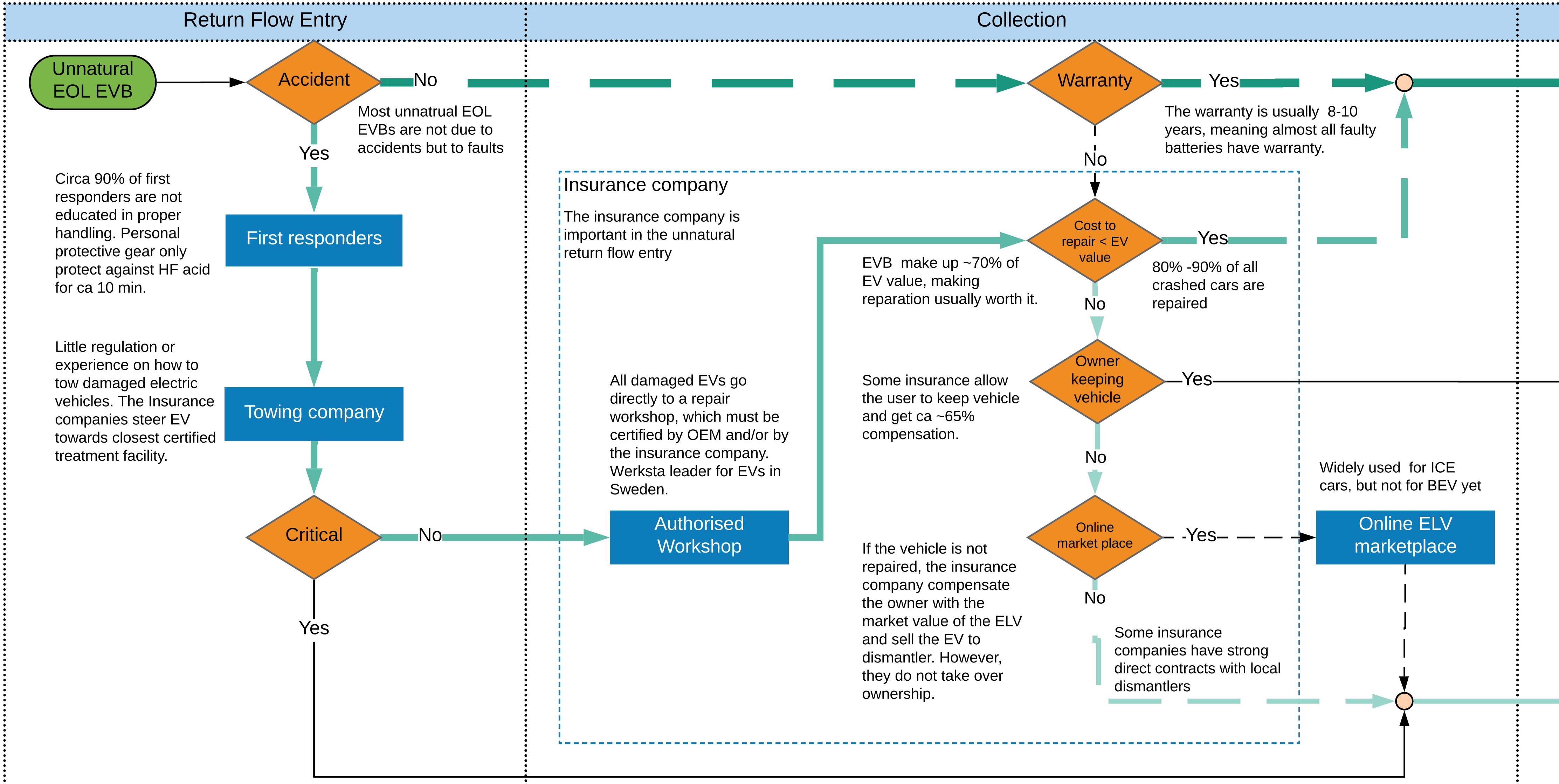
7 Appendix

First, the unnatural return flow is illustrated, followed by the natural return flow.



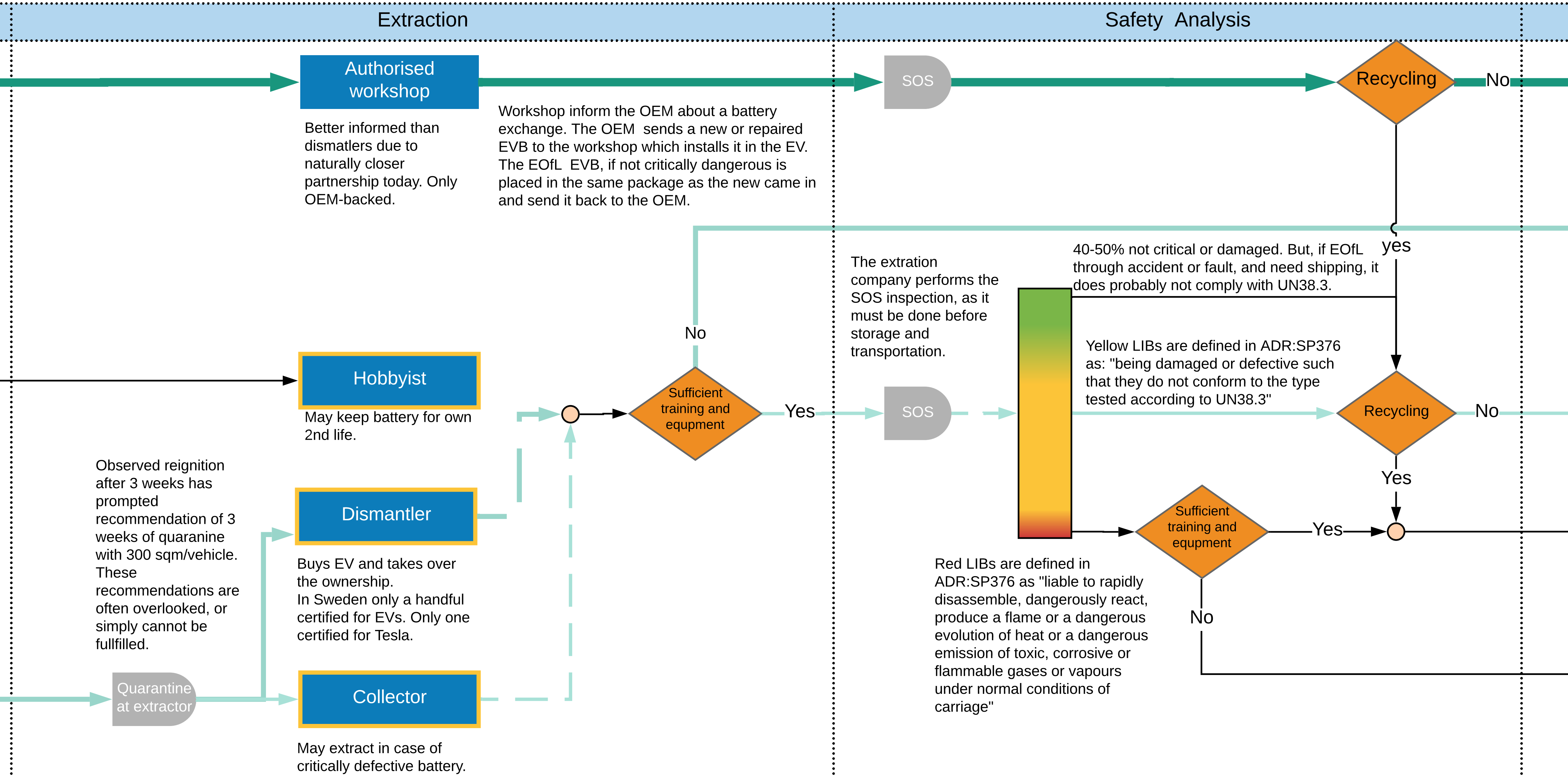
Other Findings
As the battery OEMs want their LIBs back, the auto OEMs will increasingly try and get the EVBs back. A shift from the tradtitional neglegence of EVBs from the OEM perspective

Other Findings
Today 30-40% ELVs have unknown wherabouts. To an uknown degree due of illegal export. The key problem is the lack of tracking.

Regulations to mind (both are being updated, with an expected release in early ~2022):
- The ELV directive 2000/53/EC
- The Battery directive 2006/66/EC

Auto OEMs have historically not prioritized retrieving ELVs. They have via the ELV directive only been mandated to provide proper disposal methods, should the vehicle be handed in by the owner.

Current directives implicitly sets a 100% collection-and-recycling target for EV batteries, since it is not allowed to dispose of the batteries in any way but recycling. No new target should not be established because it is difficult to relate the collection numbers to ELVs. However, the new directives should explicitly express a 100\% target.



Other Findings
The processes from safety analysis to consolidation are done by extractor today.

There are usually available extraction guides. Roughly requires 50 sqm for a car lift for extraction. Locally the extractors usually have great control, but the cradle-to-grave-traceability is usually lost. There is no general safety education for handling EVBs, but each OEM has their own courses. For a dismantler and workshop, this means that they must send every worker to each brand's respective course. All of which are basically the same. A centralized system of safety courses is important for large scale handling in the future.

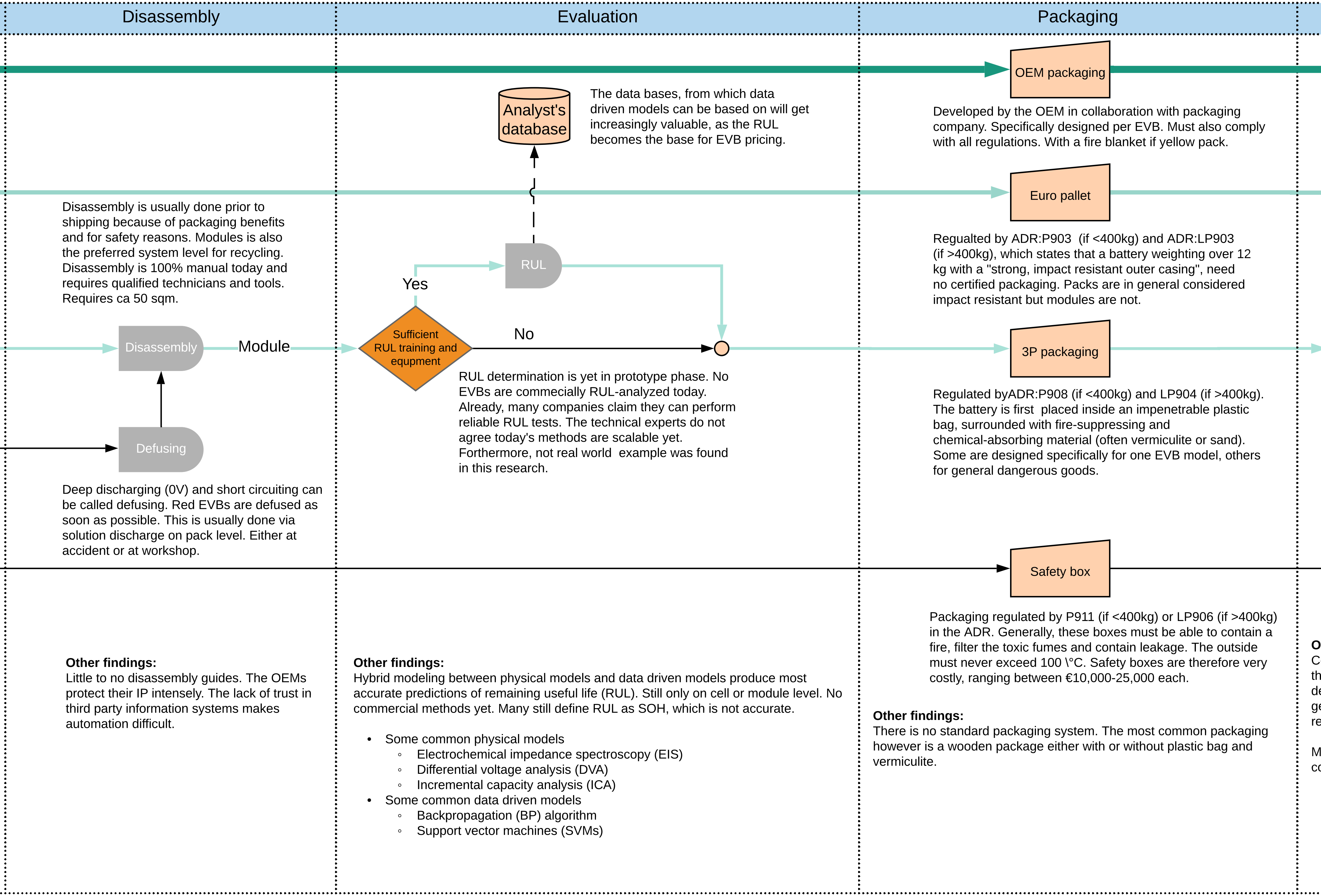
Time is always at the essence. Therefore, time consuming transportation between different actors will be suboptimal. Most of the analysis and dismantling will be done at the workshops.

Different collectors have taken different rolls. In Norway Batteriretur are hands-on, while Elkretsen in Sweden are hands-off (focus on enforcing producer responsibility)

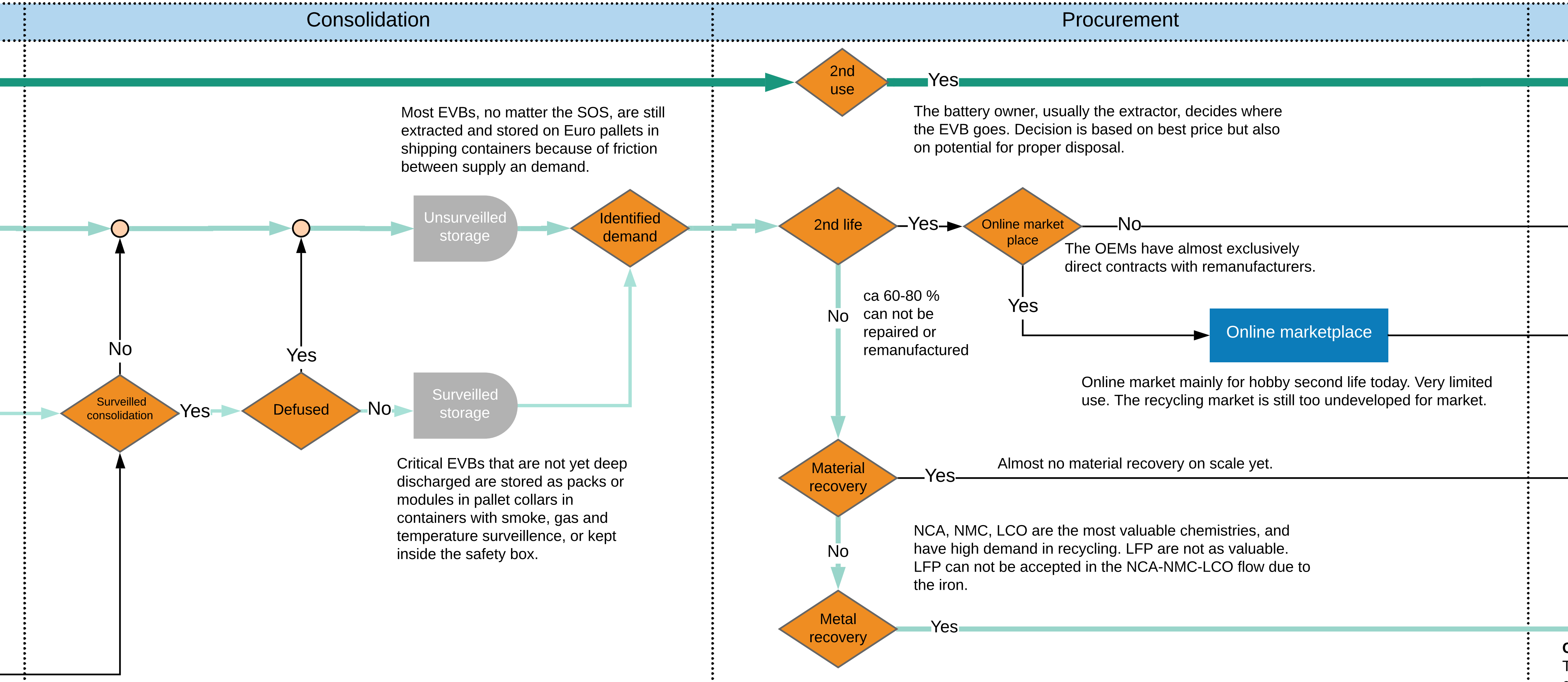
Other findings:
The state of safety (SOS) is mostly based on info from EV's system. Info gathered locally by or sometimes remotely. Classification based on historical data and personal experience. No standard method nor commercial methods for SOS analysis on pack. No way to guarantee green battery today but many assume green to lower handling costs. SOS analysis is more of an inspection in practice. It is very difficult to determine SOS other than from the vehicle's own system.

The classification of SOS is umbiguous and not universally agreed upon.

- Undamaged = Not damaged= non critical = new&used=green
- Damaged = Slightly damaged = yellow
- Critically damaged = Severely damaged = red
- EUCAR's scale from 1- 7



Disassembly
Evaluation
Packaging
OEM packaging
Analyst's database
The data bases, from which data driven models can be based on will get increasingly valuable, as the RUL becomes the base for EVB pricing.
Developed by the OEM in collaboration with packaging company. Specifically designed per EVB. Must also comply with all regulations. With a fire blanket if yellow pack.
Euro pallet
Disassembly is usually done prior to shipping because of packaging benefits and for safety reasons. Modules is also the preferred system level for recycling. Disassembly is 100% manual today and requires qualified technicians and tools. Requires ca 50 sqm.
RUL
Yes
Regualted by ADR:P903 (if <400kg) and ADR:LP903 (if >400kg), which states that a battery weighting over 12 kg with a "strong, impact resistant outer casing", need no certified packaging. Packs are in general considered impact resistant but modules are not.
Disassembly
Module
Sufficient RUL training and equpment
No
3P packaging
RUL determination is yet in prototype phase. No EVBs are commecially RUL-analyzed today. Already, many companies claim they can perform reliable RUL tests. The technical experts do not agree today's methods are scalable yet. Forthermore, not real world example was found in this research.
Regulated byADR:P908 (if <400kg) and LP904 (if >400kg). The battery is first placed inside an impenetrable plastic bag, surrounded with fire-suppressing and chemical-absorbing material (often vermiculite or sand). Some are designed specifically for one EVB model, others for general dangerous goods.
Defusing
Deep discharging (0V) and short circuiting can be called defusing. Red EVBs are defused as soon as possible. This is usually done via solution discharge on pack level. Either at accident or at workshop.
Safety box
Packaging regulated by P911 (if <400kg) or LP906 (if >400kg) in the ADR. Generally, these boxes must be able to contain a fire, filter the toxic fumes and contain leakage. The outside must never exceed 100 \°C. Safety boxes are therefore very costly, ranging between €10,000-25,000 each.
Other findings:
Little to no disassembly guides. The OEMs protect their IP intensely. The lack of trust in third party information systems makes automation difficult.
Other findings:
Hybrid modeling between physical models and data driven models produce most accurate predictions of remaining useful life (RUL). Still only on cell or module level. No commercial methods yet. Many still define RUL as SOH, which is not accurate.
• Some common physical models
◦ Electrochemical impedance spectroscopy (EIS)
◦ Differential voltage analysis (DVA)
◦ Incremental capacity analysis (ICA)
• Some common data driven models
◦ Backpropagation (BP) algorithm
◦ Support vector machines (SVMs)
Other findings:
There is no standard packaging system. The most common packaging however is a wooden package either with or without plastic bag and vermiculite.



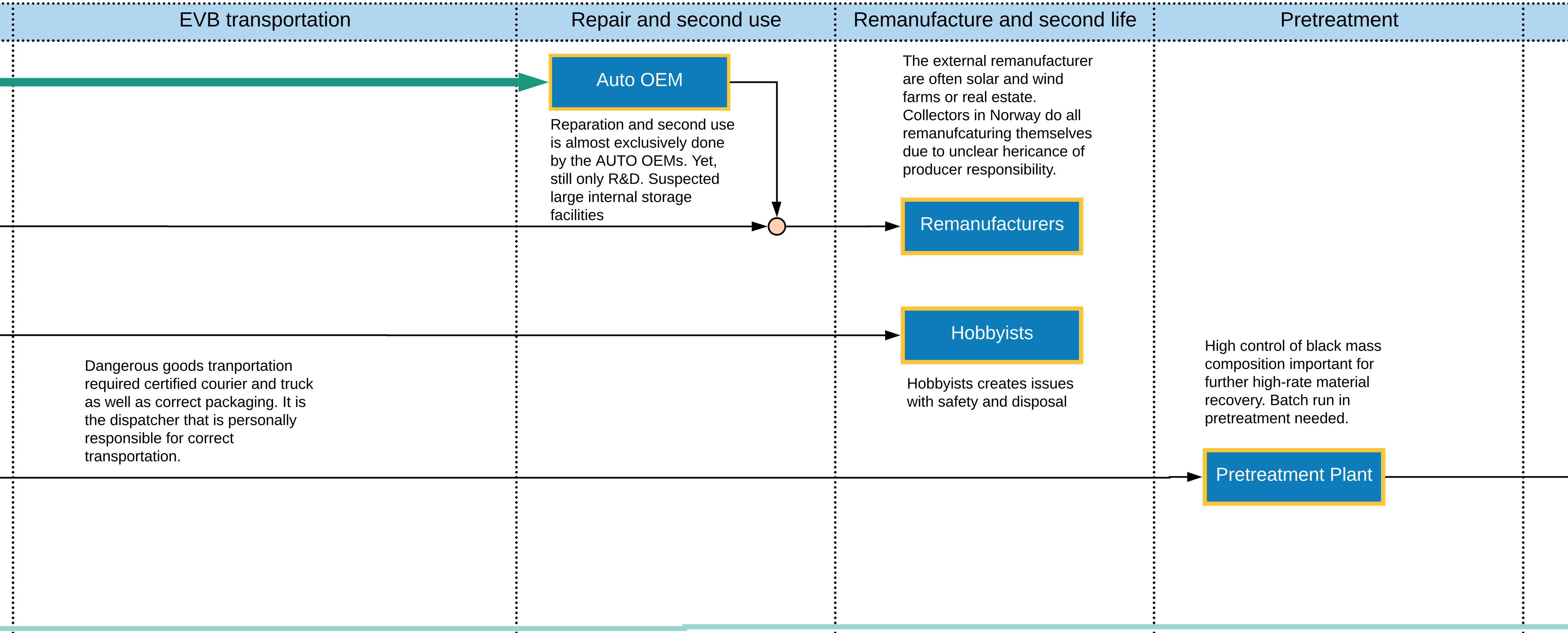
Other findings:
Consolidation is mostly done at extractor. There are few explicit storage regulations. If there are, they come from the municipality and are sometimes granted by the local fire department and environmental authority. Some argue the storage of EVBs are included in general licence for storing dangerous goods. Producer responsibility is not effective, resulting in EVBs sometimes being stored for years.

Most EVBs today that are not returned to the auto OEMs for R&D or repair, but are being consolidated in unsurveilled shipping containers in the backyards at dismantlers.

Other findings:
As the material value in batteries are falling, as does the incentives to recycle. Recycling must be covered financially by some kind of pawn-model. Today, they are covered by gate fees. Battery owners have to pay for the gate fees and here is where effective producer responsibility is key. When the owner doesn't want to carry the cost of the battery (does not profit on selling the battery), the battery owner usually contacts the collector. The collector enters into negotiations with the OEM about how they should provide or pay for disposal.

(P)HEVB are generally not interesting for second use or second life due to very low power- and energy densities compared to BEVs.

As there is no open market, few remanufacturers and recyclers know where to buy from. Large lack of knowledge about ELEVB whereabouts.



Other findings:
The individuals that pack, load and drive dangerous goods must be certified according to chapter 1.3 in the ADR. In Sweden, the punishment for illicit transportation is regulated in the legislation for transportation of dangerous goods (SFS 2006:263). In both Sweden and Germany, the individual risks fines and imprisonment up to two years. Penalties for smaller violations of transport regulations, even if no accident has occurred, are fines around €50k.

Transportation is too cheap in general. There are examples of EVBs being transported from Asia to Europe for disposal. This does not align with the environmental aspects of electric transportation

The ADR segregates between shipping As Batteries, In Equipment and With Equipment
Regulations to mind:
- The Basel Convention
- The Waste Shipment Regulation (EC) no 1013/2006 (WSR)
- The Waste Framework Directive 2008/98/EC (WFD)
- ADR (Road)
- RID (Railway)

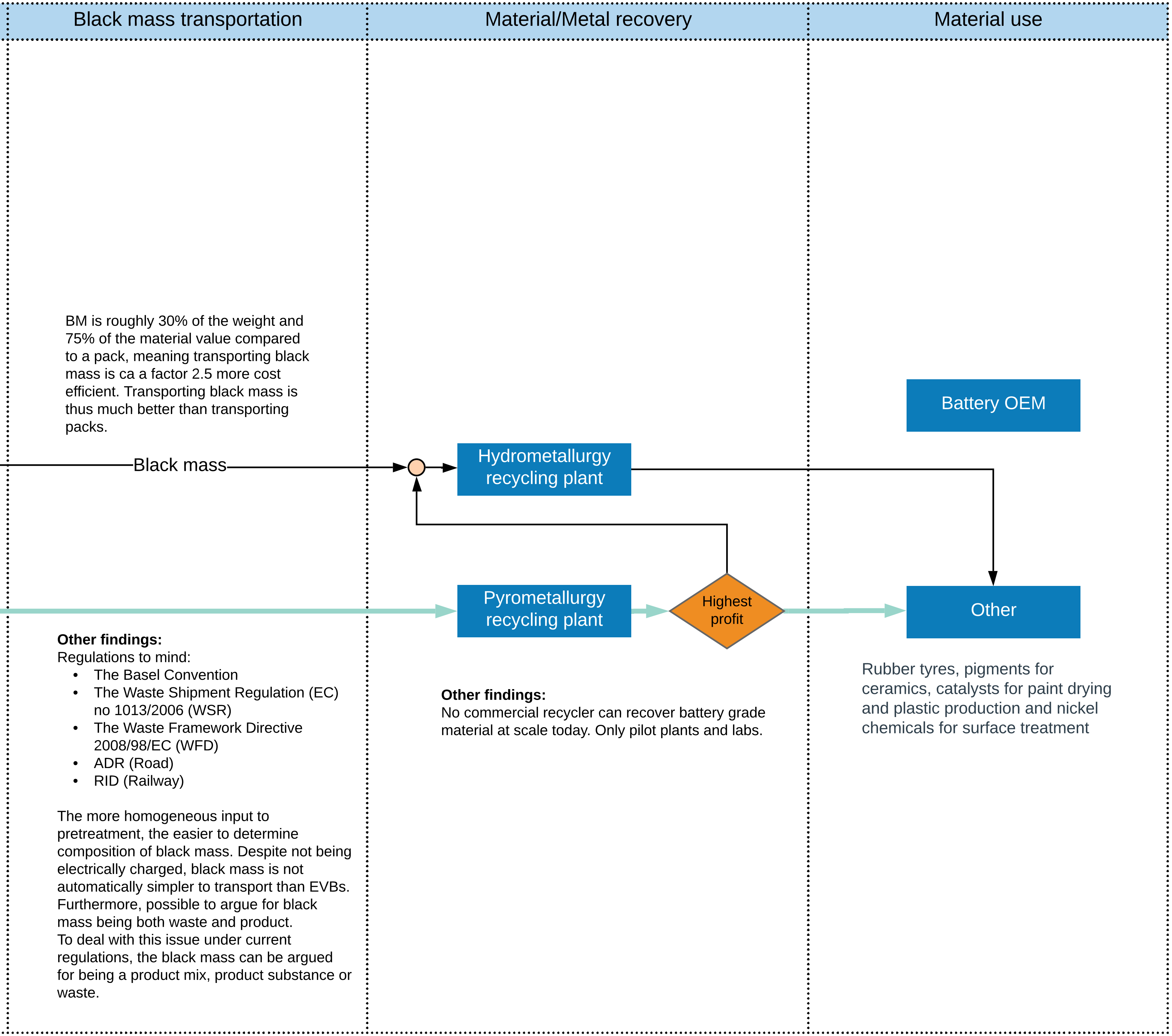
Other findings:
Highest prio for OEMs today are to repair and reuse EVBs. Then they are incentivised to recycle rather than remanufacture because of the unclear heritance of producer responsibility. On the other hand, EVs are expensive, with long depreciation time and sendeing to recycling is often last resort. This requires clearer regulations around heritance of producer responsibility.

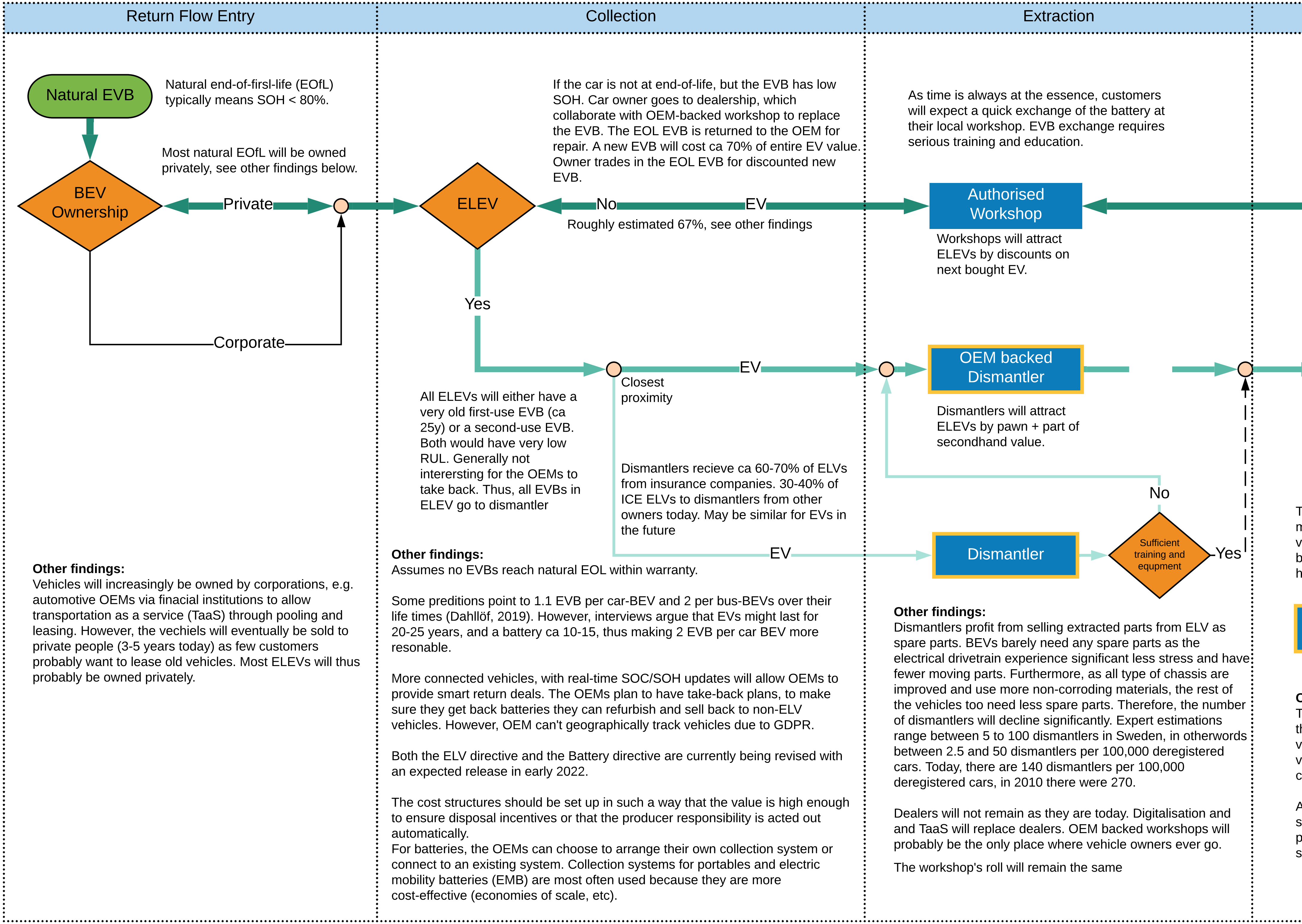
Broken electronics are not allowed to be exported for reparation, with some few exceptions that requires extensive documentation. The same rules migh be assumed for batteries. A broken EV battery may have to be repaired in the country it is located in.

Other findings:
Unclear guidelines for heritance of producer responsibility. There are very few, if any, commercial solutions yet. EVBs are designed specifically for EVs, all the way from the chemistry and cell level to the pack level. They might not always be suited for remanufacturing.

Other findings:
When classifying black mass with a European List of Waste code (ELW-code), all material fractions must be stated as a span, from which the classification is done based on the worse scenario. E.g., a mix of two hazardous components (A and B), where the concentration of A varies in the span of 30-60% and B 40-70%, the mix is classified as 60% A and 70% B to avoid having to classify the mix more than once.

To run an homogeneous input, the pretreatment plant either needs to consolidate and do batch-run, or source one type of chemistry.

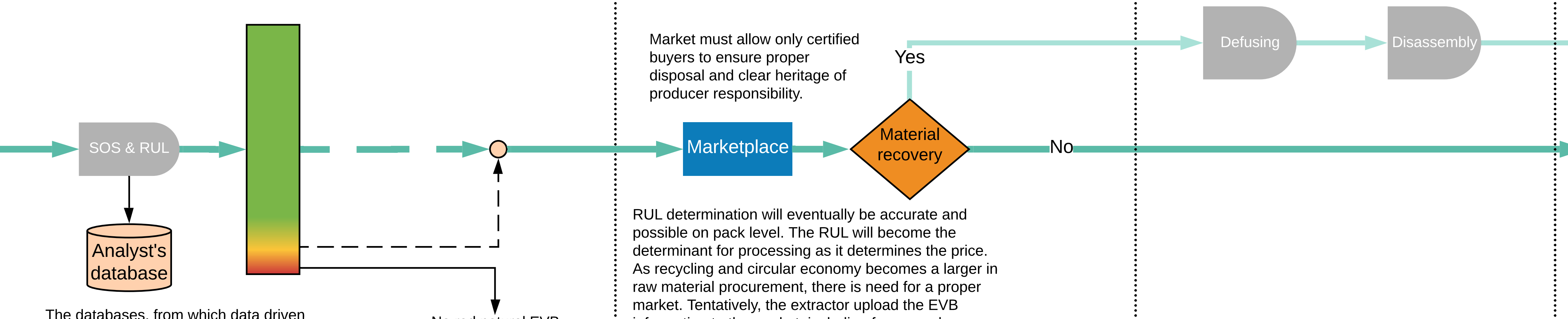

Black mass transportation
Material/Metal recovery
Material use
BM is roughly 30% of the weight and 75% of the material value compared to a pack, meaning transporting black mass is ca a factor 2.5 more cost efficient. Transporting black mass is thus much better than transporting packs.
Battery OEM
Black mass
Hydrometallurgy recycling plant
Pyrometallurgy recycling plant
Highest profit
Other
Other findings:
Regulations to mind:
• The Basel Convention
• The Waste Shipment Regulation (EC) no 1013/2006 (WSR)
• The Waste Framework Directive 2008/98/EC (WFD)
• ADR (Road)
• RID (Railway)
The more homogeneous input to pretreatment, the easier to determine composition of black mass. Despite not being electrically charged, black mass is not automatically simpler to transport than EVBs. Furthermore, possible to argue for black mass being both waste and product.
To deal with this issue under current regulations, the black mass can be argued for being a product mix, product substance or waste.
Other findings:
No commercial recycler can recover battery grade material at scale today. Only pilot plants and labs.
Rubber tyres, pigments for ceramics, catalysts for paint drying and plastic production and nickel chemicals for surface treatment



Return Flow Entry
Collection
Extraction
Natural EVB
Natural end-of-firsl-life (EOfL) typically means SOH < 80%.
Most natural EOfL will be owned privately, see other findings below.
BEV Ownership
Private
Corporate
If the car is not at end-of-life, but the EVB has low SOH. Car owner goes to dealership, which collaborate with OEM-backed workshop to replace the EVB. The EOL EVB is returned to the OEM for repair. A new EVB will cost ca 70% of entire EV value. Owner trades in the EOL EVB for discounted new EVB.
ELEV
No
EV
Roughly estimated 67%, see other findings
As time is always at the essence, customers will expect a quick exchange of the battery at their local workshop. EVB exchange requires serious training and education.
Authorised Workshop
Workshops will attract ELEVs by discounts on next bought EV.
Yes
EV
Closest proximity
OEM backed Dismantler
Dismantlers will attract ELEVs by pawn + part of secondhand value.
All ELEVs will either have a very old first-use EVB (ca 25y) or a second-use EVB. Both would have very low RUL. Generally not interersting for the OEMs to take back. Thus, all EVBs in ELEV go to dismantler
Dismantlers recieve ca 60-70% of ELVs from insurance companies. 30-40% of ICE ELVs to dismantlers from other owners today. May be similar for EVs in the future
No
EV
Dismantler
Sufficient training and equpment
Yes
Other findings:
Vehicles will increasingly be owned by corporations, e.g. automotive OEMs via finacial institutions to allow transportation as a service (TaaS) through pooling and leasing. However, the vechiels will eventually be sold to private people (3-5 years today) as few customers probably want to lease old vehicles. Most ELEVs will thus probably be owned privately.
Other findings:
Assumes no EVBs reach natural EOL within warranty.
Some preditions point to 1.1 EVB per car-BEV and 2 per bus-BEVs over their life times (Dahllöf, 2019). However, interviews argue that EVs might last for 20-25 years, and a battery ca 10-15, thus making 2 EVB per car BEV more resonable.
More connected vehicles, with real-time SOC/SOH updates will allow OEMs to provide smart return deals. The OEMs plan to have take-back plans, to make sure they get back batteries they can refurbish and sell back to non-ELV vehicles. However, OEM can't geographically track vehicles due to GDPR.
Both the ELV directive and the Battery directive are currently being revised with an expected release in early 2022.
The cost structures should be set up in such a way that the value is high enough to ensure disposal incentives or that the producer responsibility is acted out automatically.
For batteries, the OEMs can choose to arrange their own collection system or connect to an existing system. Collection systems for portables and electric mobility batteries (EMB) are most often used because they are more cost-effective (economies of scale, etc).
Other findings:
Dismantlers profit from selling extracted parts from ELV as spare parts. BEVs barely need any spare parts as the electrical drivetrain experience significant less stress and have fewer moving parts. Furthermore, as all type of chassis are improved and use more non-corroding materials, the rest of the vehicles too need less spare parts. Therefore, the number of dismantlers will decline significantly. Expert estimations range between 5 to 100 dismantlers in Sweden, in otherwords between 2.5 and 50 dismantlers per 100,000 deregistered cars. Today, there are 140 dismantlers per 100,000 deregistered cars, in 2010 there were 270.
Dealers will not remain as they are today. Digitalisation and and TaaS will replace dealers. OEM backed workshops will probably be the only place where vehicle owners ever go.
The workshop's roll will remain the same

Analysis and evaluation

The SOS and the RUL inspection is done simultaniously as they practically are the same tests and algorithms, but with different data extracted.



The databases, from which data driven models can be based on will get increasingly valuable as the RUL increasingly will be the base for EVB pricing. Machine learning highly suitable.

Other findings:
There are methods where an entire fleet sends battery data through-air during usage. There are different tracking frequencies from vehicles to the OEMs, depending on brand, country and whether the vehicle is driving, standing still or parked. Database control will be critical for leading data driven models.

As the quatitaive data models for determining RUL and SOS from stochastic remote real-time data improves, the SOS and RUL can perhaps be done before extraction, just by reading from the vehicles system.

Procurement (Urban mining)

Workshop inform the OEM about a battery exchange. The OEM sends a new or repaired EVB to the workshop which installs it in the EV. The EOfL EVB, if is placed in the same package as the new came in (with fire blanket if yellow) and send it back to the OEM.

Market must allow only certified buyers to ensure proper disposal and clear heritage of producer responsibility.

RUL determination will eventually be accurate and possible on pack level. The RUL will become the determinant for processing as it determines the price. As recycling and circular economy becomes a larger in raw material procurement, there is need for a proper market. Tentatively, the extractor upload the EVB information to the market, including for example: RUL, SOS, SOH, Geometry, Chemistry and more.

Other findings:
Procurement pushed before disassembly, packaging and consolidation.

An open secondary market would reap the benefits of circular economies without risking monopolising them.

Because of the lack of charging infrastructure, few EVs will be exported to eastern Europe or to Africa in the short term, which ICE vehicles are today. However, these countries might be quick to electrify. Perhaps they will have charging infrastructures in place in time for the big surge of ELEVs, and without proper tracing the risk for illegal export may remain.

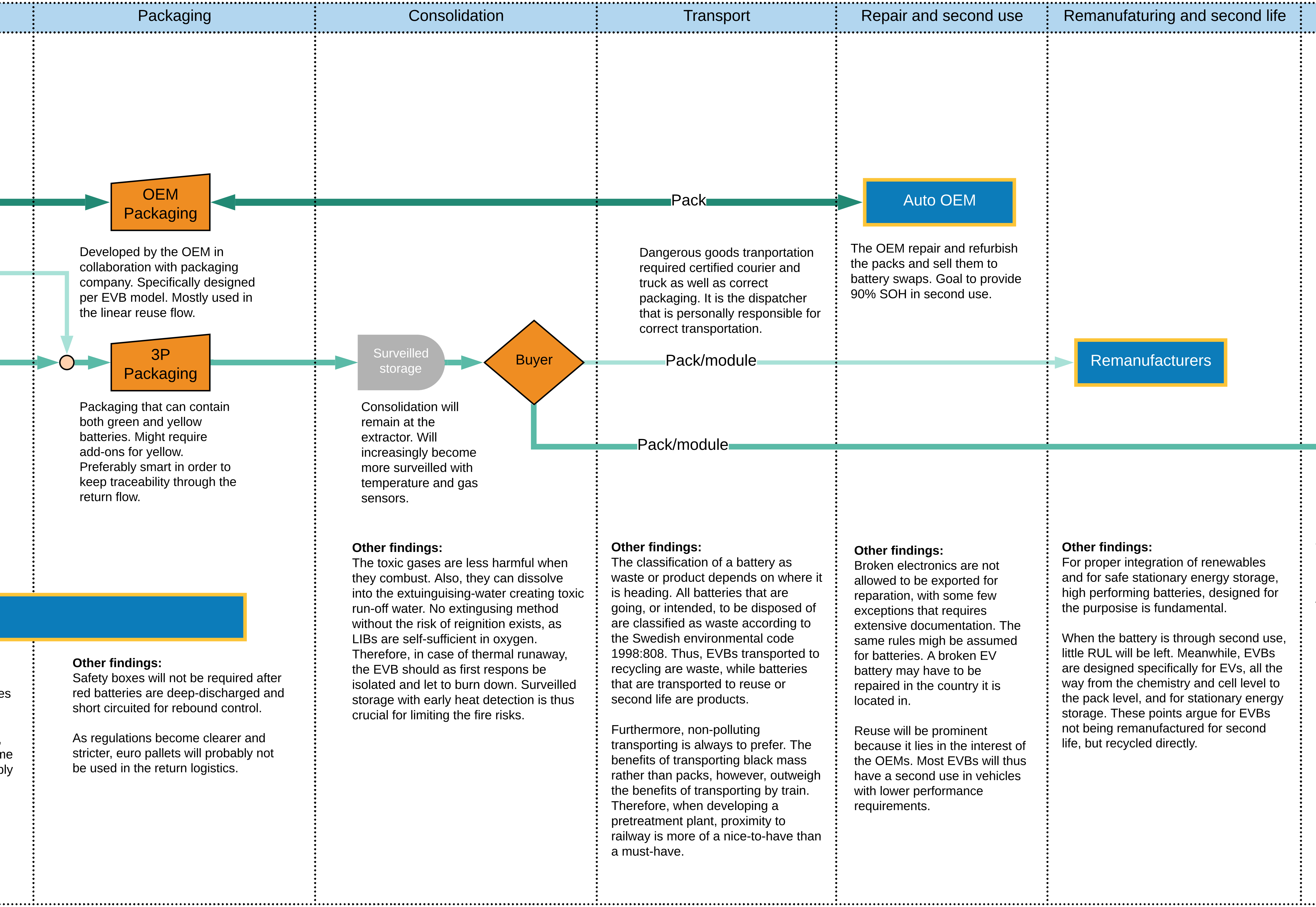
Disassembly

Disassembly may be done because of packaging benefits and for safety reasons. This step is increasingly automated and will probably be done at extractor. Module level is the preferred battery system to crush in pretreatment.

Intermediary?

Other findings:
A central disassembly guideline such as IDIS should be further developed to include EV batteries too.

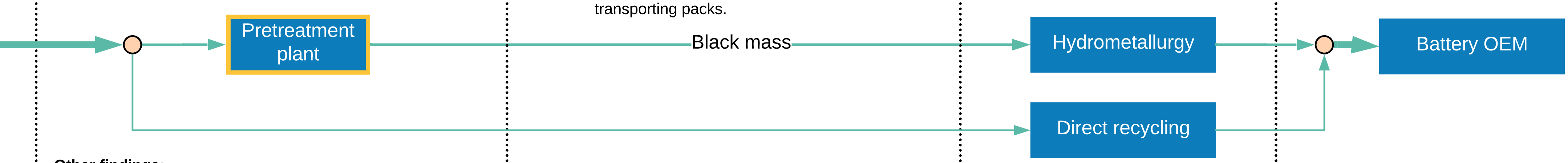
With improved packaging and clearer regulations, transporting packs rather than modules will become more popular as it removes the step of disassmebly for the extractor. Transporting on pack level also keep the BMS, which potentially can be used in second use/life.


Packaging
Consolidation
Transport
Repair and second use
Remanufaturing and second life
OEM Packaging
Pack
Auto OEM
Developed by the OEM in collaboration with packaging company. Specifically designed per EVB model. Mostly used in the linear reuse flow.
Dangerous goods tranportation required certified courier and truck as well as correct packaging. It is the dispatcher that is personally responsible for correct transportation.
The OEM repair and refurbish the packs and sell them to battery swaps. Goal to provide 90% SOH in second use.
3P Packaging
Surveilled storage
Buyer
Pack/module
Remanufacturers
Packaging that can contain both green and yellow batteries. Might require add-ons for yellow. Preferably smart in order to keep traceability through the return flow.
Consolidation will remain at the extractor. Will increasingly become more surveilled with temperature and gas sensors.
Pack/module
Other findings:
Safety boxes will not be required after red batteries are deep-discharged and short circuited for rebound control.
As regulations become clearer and stricter, euro pallets will probably not be used in the return logistics.
Other findings:
The toxic gases are less harmful when they combust. Also, they can dissolve into the extuinguising-water creating toxic run-off water. No extingusing method without the risk of reignition exists, as LIBs are self-sufficient in oxygen. Therefore, in case of thermal runaway, the EVB should as first respons be isolated and let to burn down. Surveilled storage with early heat detection is thus crucial for limiting the fire risks.
Other findings:
The classification of a battery as waste or product depends on where it is heading. All batteries that are going, or intended, to be disposed of are classified as waste according to the Swedish environmental code 1998:808. Thus, EVBs transported to recycling are waste, while batteries that are transported to reuse or second life are products.
Furthermore, non-polluting transporting is always to prefer. The benefits of transporting black mass rather than packs, however, outweigh the benefits of transporting by train. Therefore, when developing a pretreatment plant, proximity to railway is more of a nice-to-have than a must-have.
Other findings:
Broken electronics are not allowed to be exported for reparation, with some few exceptions that requires extensive documentation. The same rules migh be assumed for batteries. A broken EV battery may have to be repaired in the country it is located in.
Reuse will be prominent because it lies in the interest of the OEMs. Most EVBs will thus have a second use in vehicles with lower performance requirements.
Other findings:
For proper integration of renewables and for safe stationary energy storage, high performing batteries, designed for the purpuise is fundamental.
When the battery is through second use, little RUL will be left. Meanwhile, EVBs are designed specifically for EVs, all the way from the chemistry and cell level to the pack level, and for stationary energy storage. These points argue for EVBs not being remanufactured for second life, but recycled directly.

Pretreatment	Transportation	Material Recovery	Material Use

High control of black mass composition important for further high-rate material recovery. Batch run in pretreatment is common. With chemistry-specific procurement, on-site consolidation can be minimized.

BM is roughly 20-30% of the weight and 70-80% of the material value compared to a pack, meaning transporting black mass is ca a factor 2-4 more cost efficient. Transporting black mass is thus much better than transporting packs.



Other findings:
Pretreatement plant clustering could be beneficial for more homogeneous flows. This would minimise the consolidation. However, most recyclers want the same type of batteries. A functioning market would automatically create the homogeneous return flows, and make clustering and consolidation unnecessary.

Crushers can have a capacity of 3 tonnes/h. With the predicted returning weight in 2025, only a handfull would be needed in Europe. Preferable to have a network of smaller ones.

Nice-to-have's:
- A traceability system that allows deregistration of EVBs, increasing efforts to create full life-cycle traceability
- Close proximity to railway station or port
- Intermediate storage large enough to allow batch pretreatment to ensure a homogeneous input to recycling (or market)
- Car lift and extraction tools to allow entry of return flow at the pretreatment plant.
- A green energy mix
- Few country borders between the pretreatment plant and the material recovery plant

Other findings:
When transporting a battery from country A to country D, all countries (A,B,C and D) must be informed about the shipment. Minimizing the number of borders, may simplify the transport.

Other findings:
Regulations to mind:
- The Basel Convention
- The Waste Shipment Regulation (EC) no 1013/2006 (WSR)
- The Waste Framework Directive 2008/98/EC (WFD)
- ADR (Road)
- RID (Railway)

The more homogeneous input to pretreatment, the easier to determine composition of black mass. Despite not being electrically charged, black mass is not automatically simpler to transport than EVBs. Furthermore, possible to argue for black mass being both waste and product.
To deal with this issue under current regulations, the black mass can be argued for being a product mix, product substance or waste.