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Development Perspectives of Lithium-Ion Recycling Processes for Electric Vehicle Batteries

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DEVELOPMENT PERSPECTIVES
OF LITHIUM-ION RECYCLING PROCESSES
FOR ELECTRIC VEHICLE BATTERIES

BY
JAN ENGEL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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ABSTRACT

Over three hundred thousand battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) are currently registered in the United States (US) as of 2015, which is less than one percent of the total vehicle market share. An expected increase for electric vehicles (EV), half of all vehicles sold in the US are expected to be EVs by 2020, will inevitably lead to a high number of EV batteries reaching their end-of-life (EOL). Manufacturers must create processes to ensure a sustainable management system in order to fulfill government recycling regulations while assuming environmentally friendly processes. Recycling used EV batteries presents unique economical and ecological challenges, considering the increased volume, diversity of car batteries, and the lack of a generalizable disposal processes. Specifically, the sustainability aspect of recycling processes for EV batteries currently lacks assessment, in order to establish a more environmentally friendly and economically efficient process for battery recyclers.

Sustainability's "triple bottom line" is based on three factors: humans, the economy, and the environment. This study investigates the different recycling processes for EV lithium-ion batteries (LIB) and the associated environmental impacts and economical aspects based on the potential increased use. In order to generate the data required for an Input-Process-Output (I-P-O) model of the different processes, companies who recycle LIBs were identified. An environmental assessment of the recycling processes was performed using Life Cycle Assessment (LCA) executed via Umberto NXT LCA. The LCA explores the comparability of the disposal processes for LIBs and quantifies the process value regarding the ecological impact with regards to

the Global Warming Potential (GWP), the Human Toxicity Potential (HTP), and the Terrestrial Ecotoxicity Potential (TETP). The generated results highlighted, that a major part of the environmental impacts of the recycling processes are related to the landfill of material waste, the incineration of plastics and the generated electricity, especially for energy intensive processes, such as smelting treatment methods. In terms of environmental effects, this paper identified processes that utilize low temperatures and recover both plastics and lithium as the most beneficial processes.

To contrast the economical perspective of the different industrialized recycling processes a comparison matrix was created. The most commonly recovered materials with one of the highest values per metric ton of spent LIBs are copper, nickel, and cobalt. After determining the benefit of the different recycling processes, by evaluating the system inputs and outputs, the processes were rated on an economical level, depending on the amount of benefit generated. Overall, the recycling processes, involving different combinations of mechanical-, hydro-, and pyrometallurgical treatment steps, from five companies were compared. This paper suggests utilizing recycling processes based on a combination of mechanical and hydrometallurgical or mechanical-, pyro- and hydrometallurgical process steps, contrasting both, environmental and economic aspects. Pure pyrometallurgical treatment methods or a combination of mechanical and pyrometallurgical processes are not suggested, especially due to the absence of a lithium carbonate recovery and a resulting deposit of lithium in the slag, or a lower lithium product output.

This research is one of the few studies in this area of EV LIBs and aims to further research, by identifying environmentally friendly and economically processes for

battery recyclers. The presented results can be relevant to policy makers and recyclers since this type of waste is currently part of the European waste legislation for the treatment of Waste Electrical and Electronic Equipment (WEEE). The knowledge gained from this study will advise the recycling companies to be more conscious in their environmental behavior.

Further research can be established from this paper to assess how future LIB recycling could be examined in order to minimize the environmental impacts of recycling and how to improve the recovery of different materials. New recycling processes should be designed with a stronger orientation towards a more lithium based recovery in order to counteract a future lithium shortage.

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LIST OF ABBREVIATIONS

BEV	Battery Electric Vehicle
ELCA	Environmental Life Cycle Assessment
ELCD	European Reference Life Cycle Database
EOL	End-Of-Life
EPA	Environmental Protection Agency
EV	Electric Vehicle
GWP	Global Warming Potential
HTP	Human Toxicity Potential
I-P-O	Input- Process- Output
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LIBs	Lithium-Ion Battery (-ies)
NEEDS	New Energy Externalities Developments for Sustainability
NREL	National Renewable Energy Laboratory Data Base
PHEV	Plug-In Hybrid Electric Vehicle
TETP	Terrestrial Ecotoxicity Potential
US	United States of America
WEEE	Waste Electrical and Electronic Equipment

CHAPTER 1 – Introduction

The following paper provides a broad overview of the environmental impact and economical aspects of recycling processes for electric vehicles (EV), specifically powered by lithium-ion batteries (LIBs), and discusses the end-of-life (EOL) issues utilizing Life Cycle Assessment (LCA). The LCA explores the comparability of the disposal processes for LIBs and quantifies the process value regarding the ecological impact. Additionally, economical aspects are considered, in order to identify environmentally friendly and economical efficient processes for LIB battery recycling.

This first chapter presents the background and current research gap of this topic area. Furthermore, the goal of this study is described and the approach presented.

1.1 Background and Motivation

Even though the target set by the United States (US) government of having one million electrically operating vehicles by 2015 has not been achieved (DOE U.S., 2015; Trigg et al., 2013), the number of registered electric vehicles will rise continuously and will inevitably lead to an increased number of multiple types of EV batteries reaching the EOL (Trigg et al., 2013; Zhou, 2014; Standridge & Corneal, 2014). The US lithium demand in 2050 is expected to be over 50,000 metric tons (Gaines & Nelson, 2009; Standridge & Corneal, 2014). Figure 1 shows the world lithium demand over time for different battery sizes, stating that vehicles with large batteries (12 – 18 kWh) would cause the demand to rise to about 500,000 metric tons in 2050.

Figure 1. Worldwide Lithium Demand (Gaines & Nelson, 2009)

Dismantling and recovering of all automotive vehicles need to meet a minimum standard of 95% of the average vehicle weight in the EU currently (EU ELV Directive) (2000/53/EC, 2016). The battery weight (approximately 1200 lbs.) in relation to the total car weight (approximately 4800 lbs.) of a TESLA Model S (Roper, 2015), for example, is approximately 25%, meaning the battery must be a part of the recycling process. Europe is the only region in the world, having extended laws in the area of recycling. The US handles laws regarding recycling by state, only California and New York are actually considering lithium-ion batteries (Gaines, 2014), and those are classified as hazardous waste being subject to requirements concerning packaging, labelling, and shipping (Gaines, 2014). The recycling process of these used batteries present an economical and ecological challenge considering the increased volume and diversity of car batteries (e.g., lead-acid batteries, nickel-cadmium batteries, nickel-metal-hybrid batteries, sodium-sulfur batteries, and LIBs), with no generalizable disposal process. The development of a disassembly and recycling network is necessary

to collect and recycle huge amounts of spent batteries effectively (Zeng et al., 2014; Fleischmann et al., 2000).

Several globally operating industrialized recycling processes are present, that are able to disassemble and recycle LIBs. Companies in Europe (i.e., Germany, Switzerland, France) and the US currently carry out various recycling processes. The recycling of EV batteries will gain in significance in the near future, due to the increasing demand of lithium and the corresponding lithium shortage, as previously described, thereby, the environmental impact of current industrialized recycling processes need to be analyzed.

1.2 Research Goal and Structure of the Paper

While Life Cycle Assessment (LCA) and the general recycling of lithium-ion EV batteries are both areas which are well investigated, the combination of both terms is limited in scientific research. A consideration of industrialized recycling processes for EV LIBs and a comparison of those regarding the economical and environmental impact using LCA has not been investigated.

The goal of this paper is to analyze the environmental impact and economical aspects in relation to the produced outputs of existing industrialized recycling processes for EV LIBs and therefore the suggestion of a preferential recycling process. In the end, a recycling process in the area of EV LIB recycling shall be identified, having the lowest environmental impact (i.e., Global Warming Potential [GWP], the Human Toxicity Potential [HTP], and the Terrestrial Ecotoxicity Potential [TETP]) and working economically efficient. A LCA is performed exploring the comparability of the

recycling processes for EV LIBs and quantifies the process value regarding the ecological impact.

This paper will determine the environmental impact and economical aspects of the industrialized recycling processes for EV LIBs via LCA. This research will focus on lithium-ion batteries only; other battery chemistries are eliminated due to the predominant use of LIBs for EVs as shown in Figure 1 (Chagnes & Swiatowska, 2015; EPA, 2013).

Thereby, the following research questions are addressed:

- What recycling processes are currently recycling EV LIBs at an industrial level?
- What are the process-based differences between these industrialized recycling processes?
- What is the measurable environmental impact and economical benefit of these recycling processes for EV LIBs?
- Which current EV LIB recycling processes are superior in relation to the environmental impact and economical benefit?

The overall procedure being followed in this research study is illustrated in Figure 2, with the timeline on the left hand side. The thesis is divided into five sections. After introducing the subject of this paper and formulating the research problem, the following Chapter 2 differentiates the context from previous research. The theoretical basis of this paper is described, providing fundamental knowledge of LIBs in general, the currently existing industrialized recycling processes for EV LIBs.

The third chapter introduces the methodology used to analyze the environmental impact of the processes. This includes the identification of potential indicators for the environmental impact and collection of appropriate data for the different processes, as well as selecting the suitable LCA software. Additionally, this chapter states the framework to compare the processes on an economical basis.

In the fourth chapter, all relevant data is implemented into the LCA modeling software Umberto and executed per recycling process. LCA is a common method to evaluate the environmental impact of a product during its life cycle (Baumann & Tillmann, 2004; ISO 14040, 2006). Additionally, the results will be analyzed and a discussion of the results regarding the environmental impact and economical aspects will be performed.

The last chapter includes a final conclusion and recommendations regarding the choice of particular recycling processes and potential future research fields within the recycling of EV LIBs.

Figure 2. General Overview of the Procedure of the Study

CHAPTER 2 – Literature Review

The following chapter gives an extensive review of the current state of the art industrialized recycling processes for EV LIBs and differentiates the context of this work from previous research. The theoretical basis of this paper is described, providing fundamental knowledge of sustainability.

The global concern and focus on spent LIBs is still increasing, in the past 10 years over 200 papers and 100 patents related to recycling technologies and processes have been created, first in laboratory scale and subsequently on an industrialized level (Zeng et al., 2014). Figure 3 depicts the increasing attention concerning spent LIBs from 2000 until 2012 in publications and shows the percentage of recycling unit operations being talked about within publications. The distribution is partly indicative for this research, four out of five companies are undergoing mechanical and hydrometallurgical process steps, and three out of five recycling companies are working with pyrometallurgical treatment methods. No company, currently, is considering bio-treatment within their recycling processes.

Figure 3. Global Concern Related to Spent LIBs (Zeng et al., 2014)

A copious amount of literature (approximately 1066 research articles) is available online based on the “Web of Science” (Reuters, 2015), considering battery recycling. This literature is addressable in numerous literature databases, such as the used database Web of Science, or IEEE Xplore, and Inspec. In order to get a general overview of existing literature, the online web service “Web of Science” is used. Web of Science is a citation indexing service provided by the entrepreneur Reuters, that provides a comprehensive citation search online. It offers admission to numerous databases that reference cross-disciplinary research, which permits for profound exploration of specialized fields within an academic or scientific discipline (Reuters, 2015). The interest in electric vehicles and therefore the increasing need for sustainable recycling processes are widely discussed. To specify the amount of literature used, different catchwords, such as “recycling batteries” or “battery recycling”, are made up to isolate the critical mass of the current research paper. Starting with the number of 1066 articles concerning the battery recycling between 2005 and 2015, these cited articles are filtered in subsequent stages. Mainly those articles remained, that focused on the recycling of lithium-ion batteries, resulting in 37 remaining articles. Further filtration of the research literature towards this research topic, led to eleven articles which are directly focusing on battery recycling processes for EV LIBs (Reuters, 2015). All other articles focused on the recycling of portable LIBs or different battery types. Figure 4 illustrates the filtration of used literature based on the “Web of Science” website, in order to set up the frame and show the limited amount of information of the research topic.

Figure 4. Classification of Research Topic – Recycling LIBs of EVs

Overall, this paper focused on over 90 sources from various databases, including journal articles, conference papers, books or internet sources, directly or indirectly related to areas, such as to electric vehicles, battery recycling, EV battery recycling or EV LIB battery recycling.

Considering the research topic, there is no current knowledge of the comparison among existing industrialized recycling processes for EV LIBs evaluated via LCA based on environmental and economical impacts.

2.1 Basics of Lithium-Ion Batteries

This section gives a description of EV LIBs in terms of use, applications, and composition, in order to gain knowledge about the functioning of the battery, before investigating the actual recycling processes.

2.1.1 Structural Design of LIBs

Most battery systems pursue a similar structural design. Besides battery modules, more specifically battery cells, the basic components of battery systems are the battery management unit, other electronics and casing/connecting components.

Figure 5. Components of a General Battery System (Hanisch, 2014)

The most common battery technologies for EVs are lead-acid batteries, nickel-cadmium batteries, nickel-metal-hybrid batteries, sodium-sulfur batteries, and LIBs (Gaines, 2014). LIBs are used extensively due to exhibiting superior cycle life compared to similar technologies (Korthauer, 2013), showing the highest specific energy density of up to 200 Wh/kg, a constant voltage discharging process, a low self-discharging rate over time, and are simple to charge and maintain. The LIB type therefore fits the upcoming requirements (e.g., charging time and driving range) regarding electric vehicles the best (Zeng et al., 2014). LIB cells are assembled in battery modules, which are subunits of the entire battery system. An extremely high number of cells are packed together in a single plastic case, connected into modules with control circuitry attached. Figure 5 shows the components of a general battery system, consisting of casing and

connecting components, a battery management unit and other electronics, as well as battery cells, which are connected into modules.

The basic components of a lithium-ion cell are an anode, a cathode, an electrolyte and a separator (Zeng et al., 2014; Korthauer, 2013). The anode is a copper foil, covered with graphite. Carbon is usually the active anode material in batteries, it is bound onto a copper conductor plate using a polymeric binder (Zeng et al., 2014). The cathode conductor plate is composed of an aluminum foil covered with an electrochemically active material. LIBs are using various types of cathode materials. The fundamental component is always a lithium-transition-metal-oxide (LiMO_2) used in automotive applications, such as the most common material lithium cobalt oxide (LiCoO_2), lithium manganese oxide (LiMn_2O_4), lithium nickel oxide (LiNiO_2), lithium vanadium oxide (LiV_2O_3), and LiFePO_4 (Kang et al., 2006). The Chevy Volt for example uses a Mn-spinel and mixed metal cathode, the Coda Sedan uses LiFePO_4 , the Nissan Leaf uses LiMn_2O_4 and the Tesla Model S uses LiCoO_2 (Fletcher, 2011; Schneider, 2007; Hernandez, 2011; Lucas, 2012). All active electrode materials are set up of granulates and fixed onto the collector plates using a binder. The binder needs to be resistant against both heat and electricity. An electrolyte is required to allow an ionic transport between the electrodes; it represents the medium through which ions diffuse to create energy by travelling from one electrode to the other (Bernardes et al., 2004). For ionic conductivity electrolytes need to contain lithium salts. Solvents that are able to emit various lithium salts are required. The separator keeps a certain distance between the anode and cathode and prevents short-circuiting from direct contact of the electrodes and functions as a safety device (Zeng et al., 2014).

Figure 6 illustrates the function of a LIB, the lithium-ion technology is based on a lithium-ion movement between the anode and cathode, forcing electrons to move between them (Alper, 2002). During the discharging process Li-atoms emit electrons on the anode side leaving positive charged Li-ions behind. Electrons flow through the external electrical circuit from the anode to the cathode. At the same time Li-ions travel across electrolyte fluid through the separator to the cathode due to electrical attraction. The induced potential difference is the driving force that lithium-ions move towards the positively charged cathode. This prevents the cathode to be negatively charged and electrons to be repelled, which would lead to a current flow stop (Hoyer, 2015; Maehliß, 2012). During the charging process the whole operation is reversed.

Figure 6. Schematic Function of a Lithium-ion Battery
(Hanisch et al., 2013)

Due to moving Li-ion during the charging and discharging process the cells are called Li-ion cells. Li-ion cells do not use metallic lithium due to potential short circuit, instead active materials on the anode side are used. The cathode side uses a metal oxide, such as cobalt oxide or manganic oxide, to generate a high potential difference. Both

graphite and metal oxides are structured in layers, so that the Li-ion can be stored in between the layers (Maehliß, 2012).

The various material compositions of LIBs, especially regarding the different types of cathode materials, such as LiMO_2 , LiCoO_2 , or LiFePO_4 (Kang et al., 2006), or dealing with harmful and dangerous components, make the processes for the battery recyclers more complex (Xu et al., 2008).

2.1.2 Reasons for LIB Recycling

The most prominent reasons for LIB recycling and the fulfillment of electric waste laws are the recovery of valuable materials, such as nickel, cobalt, and copper. Battery recycling is strongly price driven (Kumar, 2014), and materials are often only recovered if they can be sold and result in profit. Some materials are more valuable than others, and therefore worth recovering as shown in Table 1, clearly stating, that lithium carbonate is not as valuable in terms of price than cobalt or nickel.

Table 1. Valuable Materials in Battery Systems based on the Current Price (2016)

Material	Current Price (US\$/ m ton)	Source (2016)
Nickel	8,960.0	(InvestmentMine, 2016)
Cobalt	23,800.0	(InvestmentMine, 2016)
Aluminium	1,591.9	(InvestmentMine, 2016)
Copper	4,692.1	(InvestmentMine, 2016)
Steel	300.0	(Quandl, 2016)
Lithium Carbonate	6,000.0	(Lithium Investing News, 2016)

Market fluctuations cause the market prices of materials to vary over time. The materials primarily recovered by recyclers, such as cobalt, nickel, and copper, are noticeably decreasing in value (InvestmentMine, 2016). Instead the market price for lithium is continuously rising, due to an increasing worldwide lithium demand and a predicted future shortage of lithium (Gaines & Nelson, 2009). The changes in market prices for valuable materials are giving recyclers the opportunity to focus more on lithium recovery, while still utilizing economical advantageous processes.

Additionally, the disposal of EOL vehicle batteries is regulated by law, especially in Europe (EU Directive: by 2016 45% of used batteries must be collected and recycled each year [2000/53/EC, 2016]), which must be taken into account by the producing manufacturers (Kampker et al., 2013). Governments have strict regulations on the disposal of rechargeable LIBs. Europe is the only region in the world, having extended laws in the area of recycling. Dismantling and recycling vehicles need to meet a minimum standard of 95% of the average vehicle weight in the EU currently (2000/53/EC, 2016). This legislation affects all materials being recovered, meaning that the recovery of just copper, nickel and cobalt would not achieve the required recycling efficiency and therefore more materials must be recycled. The US Environmental Protection Agency (EPA) regulates the disposal of batteries in large quantities under the universal rules of hazardous waste (40 CFR PART 273) (GPO, 2012). There are no federal regulations for the disposal of LIBS, therefore each state is establishing their own guidelines (GPO, 2012). Only California and New York are actually considering lithium-ion batteries (Gaines, 2014), and those are classified as hazardous waste being subject to requirements concerning packaging, labelling, and shipping (Gaines, 2014).

2.1.3 Battery Recycling Steps

A generic recycling process for LIBs of EOL electric vehicles can generally be structured as a sequence of collecting, sorting, handling, eliminating, and distributing, with the goal of recovering useful battery materials (Fleischmann et al., 2000). A manufacturer can process the batteries themselves or be a part of a cooperative recycling network. The basic principles of an industrialized recycling process for EV batteries are illustrated in the Figure 7.

Figure 7. Industrialized Recycling Processes for EV LIBs (Hoyer, 2015)

Figure 7 shows the different stages in the EOL phase of an EV battery. After the spent batteries are removed from the vehicles and transported to the recyclers, they are separated into the different battery components. Subsequently, the spent batteries are processed using different treatment operations (i.e., mechanical-, hydro-, pyrometallurgical treatment) and the refined materials are shipped to manufacturers. Those recovered materials are used to create new batteries, which are then installed into

new automobiles. This paper is focusing on those different ways to recycle EV batteries; step 4 in Figure 7.

Currently, there are different methods to recycle LIBs, which combine various process operations. As shown in Figure 8 in those methods, batteries are first mechanically processed, and then hydrometallurgically and pyrometallurgically treated (Bernardes et al., 2004; Espinosa et al., 2004).

Figure 8. Recycling Unit Processes for EV LIBs

The different process paths are always a combination of deactivation, mechanical treatment, hydrometallurgy, and/or pyrometallurgy (Fleischmann et al., 2000). Often the deactivation step is considered to be part of the mechanical treatment step, and is therefore not mentioned separately. Opening LIBs is potentially hazardous, the deactivation step is used to minimize the risk of potential chemical reactions of charged LIBs. Deactivation covers thermal pretreatment, or a discharging step to reduce the hazard level, as well as freezing of the electrolyte to prevent further electrochemical

reactions. During the mechanical preparation process, LIB packs are disassembled into single components and often manually dismantled or shredded (Weyhe [B], 2012; Weyhe [A], 2012). The mechanical treatment implies the crushing of batteries to open cells and modules in order to sort and classify valuable materials, such as copper foil, aluminum foil, separator, and coating materials. This is usually done by a rotating blade or hammer (crushing). The separation of crushed components is also part of the mechanical process; materials are sorted in relation to their actual physical properties. Air ballistic separation separates light and heavy materials and magnetic separation extracts ferrous components, sieving and vibrating tables can also be used to separate materials (Hoyer, 2015). The mechanical treatment is a pre-step for following processes (Al-Thyabat, 2013). In pyrometallurgical processes, various components of battery cells are liquefied using high temperatures (Bernardes et al., 2004). These processes enable the recovery of the transition metals nickel, cobalt, and copper, while lithium and aluminum remaining in the slag. Pyrolysis, smelting, distillation and refining are just a few thermal treatments being used during pyrometallurgical processes. Due to the need of high temperatures during this recycling process, large amounts of energy are consumed (Bernardes et al., 2004). Lithium is not recovered by the pyrometallurgical process, it remains in the slag and must be treated hydrometallurgically to recover lithium in the end. Hydrometallurgical processes are used to recover pure metals from coating materials, either from mechanical processes or from the resulting slag from the pyrometallurgical processes (Zeng & Li, 2013; Hanisch et al., 2013). Hydrometallurgical recycling processes are considered appropriate for the recovery of

metals from LIBS, due to the good purity, low energy requirements and minimal air emissions (Xu et al., 2008).

2.1.4 Industrialized Recycling Processes for LIBS

Globally operating recycling companies are able to disassemble and recycle LIBs are reviewed. Companies and research institutes capable of recycling LIBs are discovered in Europe (i.e., Germany, France, and Switzerland), and the United States. An overview of current industrialized processes is depicted in the research papers of (Georgi-Maschler et al., 2012) and (Vezzini, 2014). Different combinations of unit operations (i.e., deactivation, mechanical treatment, hydrometallurgy, and pyrometallurgy) result in different industrialized recycling processes for each company (Hanisch et al., 2015). All industrialized recycling processes for EV LIBs differ in certain ways, that comprise a broad variety of methods, due to the fact that the continuous development of battery systems in the area of design or materials has resulted in the lack of a standardized industrial recycling process (Weyhe [B], 2012). The globally operating recycling companies in the area of EV LIB recycling are reviewed in a more detailed way. Those companies are frequently mentioned in the literature, journals, reports, and in the media with a recognizable influence on the global market (Gaines, 2014; Zeng et al., 2014; Bernardes et al., 2004; Espinosa et al., 2004; Vezzini, 2014; Hanisch et al., 2015).

Companies 1, and 2 are using processes with the same basic unit operations: mechanical treatment and hydrometallurgical processing. EV LIB recycling is a relatively new business field for Company 3, using a combination of mechanical

treatment and pyrometallurgy. Company 4 insists on the recovery of materials by utilizing only pyrometallurgical process operations, whereas Company 5 incorporates all four processes mentioned: deactivation, mechanical treatment, and both hydro- and pyrometallurgical processing (Zeng et al., 2014; Weyhe [B], 2012). To get a general overview of the comparability of the different industrialized recycling processes, the following Figure 9 shows an oversimplified visualization.

Figure 9. Unit Operations of Industrialized Recycling Processes for EV LIBs

Comparing the different unit operations of the recycling companies, similarities become visible. Even though the general treatments are mostly similar, the methods within these processes differ. The following Figure 10 illustrates the similarities and differences within the mechanical treatment and hydrometallurgical process by analyzing the recycling steps of Companies 1, and 2. Additionally, some input and output material streams of the specific processes are taken into account and visualized, as shown in Figure 10.

The amount of data given strongly relies on the available data output given by the analyzed recycling companies based on their websites or the reviewed literature (Gaines, 2014; Bernardes, 2004; Espinosa, 2004; Hanisch, 2015). The main difference in the mechanical treatment phase between these companies is the way the materials are treated in order to reduce risks of explosions. Company 2 is crushing the batteries in a gaseous atmosphere, whereas Company 1 is pursuing a different approach by cooling down the batteries in a cryogenic cooling process (Dunn et al., 2012). During the hydrometallurgical treatment phase, Company 2 is undergoing a leaching, and precipitation treatment step, whereas Company 1 is focusing on filtering and an evaporation step (Dunn et al., 2012).

Figure 10. Unit Operations/Material Flow: Company 1 and Company 2

The recycling process of Company 3 is based on a combination of mechanical treatment and pyrometallurgical processes to recycle LIBs. Similarities of Company 3 and Company 2 are noticeable in early process stages, in which the batteries are crushed

in an inert gas atmosphere and undergo similar separation steps. In the following process steps the unit operations differ from the previous discussed Companies 1, and 2. The spent batteries are undergoing leaching, and pyrolysis steps, creating metal fractions, and lithium oxides. The main difference is the recovery of a lithium oxides by Company 3, instead of lithium carbonate as produced by Companies 1, 2, and 5 (Cheret & Santen, 2007). The following Figure 11 illustrates the specific processes within the mechanical and pyrometallurgical unit operations of Company 3's recycling process in a simplified way. Additionally, all given data input and output material streams are visualized.

Figure 11. Unit Operations/Material Flow: Company 3

By contrast, recycling Company 4 only relies on pyrometallurgical processes to recycle LIBs, and is therefore utilizing a different approach compared to Companies 1, and 2. Similarities of Company 4, and Company 3 are noticeable in comparable leaching treatment methods, in all following process steps the unit operations differ from the

previous discussed Companies 1, 2, and 3. In comparison to Company 5 a similar smelting process step is executed, in which the EV scrap undergoes a similar smelting process in a furnace. The spent batteries are smelted in a furnace, creating valuable alloys. The main difference is the absence of a final lithium recovery, which remains in the produced slag (Cheret & Santen, 2007). Slag describes a stony waste product separated from metals during smelting processes. The following Figure 12 illustrates the specific processes within the pyrometallurgical unit operation of Company 4's recycling process in a simplified way. Additionally, all given data input and output material streams are visualized.

Figure 12. Unit Operations/Material Flow: Company 4

Company 5 demonstrates a recycling process for EV LIBs in which all unit operations are used at least once during the disposal and recycling process. Besides similar crossings in the pretreatment phase, such as the partial dismantling, the methods and material streams differ within the unit operations. Figure 13 illustrates the recycling

process for EV LIBs of Company 5, besides showing the specific methods used within all treatment phases. All given data concerning material input and output streams are visualized (Figure 13). The main difference between Company 5 and the previous discussed Companies 1, 2, 3, and 4 is the usage of all different process steps, such as crushing and separation, but also smelting in a furnace and a final leaching step. The biggest difference is the usage of a vacuum thermal pretreatment as a deactivation step, in which the electrolyte gets evaporated (Chagnes & Swiatowska, 2015).

Figure 13. Unit Operations/Material Flow: Company 5

All recycling processes for EV LIBs show comparable elements. Analyzing the specific unit operations in a more detailed way, it is difficult to make a statement about the comparability due to the company-based differences (Zeng & Li, 2013). Even though basic unit operations of industrialized EV LIB recycling processes are identical, this does not indicate that the actual processes within these units are the same. The amount of information makes it hard to specifically describe each recycling step and

material flow, making it challenging to compare these processes. Even though all reviewed recycling processes run on an industrialized basis, there is just a limited availability of data.

Due to a continuous development of battery systems in the area of design or materials, no standard recycling process for EV LIBs exist on an industrial-base currently (Korthauer, 2013; Espinosa, 2004). Uncertainty factors in the areas of metal prices, recycling processes, battery lifespan, and prevalent LIB technology will influence the development process.

2.2 Value Theory of Recycling Processes for LIBs

A previous paper focused on the application of value theory to the industrialized recycling processes for EV LIBs (Engel & Macht, 2016). The purpose of establishing value for a particular process is to see if a process is either more powerful than another or more generalizable.

To quantify the process value of recycling EV LIBs via Value Theory (Table 2), three different criteria have been established. Each criteria is valued with a specific weight, depending on the importance of the process, and treated in an additive model, as they are mutually and preferentially independent. The criteria evaluated are the recycling efficiency, the CO₂ recycling saving potential, and the recycling capacity. The criteria weights are scale-based, depending on the reviewed literature and authors' assessment. A scale from 1 to 9 (i.e., scale = {1, 3, 5, 7, 9}) is set up to rate the previously established criteria for the different recycling processes of each company. Within a specific interval, the criteria are graded according to the scale demonstrated in Table 2.

In the end, the goal is to get a process rating value and quantify the different industrialized processes.

Table 2. Value Theory – Companies Recycling Processes for EV LIBs

Companies Recycling Processes (RP) for Lithium-Ion EV Batteries	Recycling Efficiency Lithium-Ion EV Batteries (W ₂) x 3 WF (Weighting)	CO ₂ Recycling Saving Potential (W ₃) x 2 WF (Weighting)	Recycling Capacity Lithium-Ion EV Batteries (W ₁) x 1 WF (Weighting)	Process Rating PR = $\sum (X_i \cdot W_i)$
RP - X1 Company 1	50% (target) ?	? ?	? ?	?
RP - X2 Company 2	50% (target) ?	? ?	2.300 t 3	?
RP - X3 Company 3	50% (target) ?	? ?	5.000 t 5	?
RP - X4 Company 4	> 50% (current) 1	? ?	4.000 t 5	?
RP - X5 Company 5	> 50% (current) 1	? ?	7.000 t 7	?
Value Theory Scale = { 1,3,5,7,9 }	< 60 60 - 70 70 - 80 80 - 90 90 <	1 3 5 7 9	< ? ? - ? ? - ? ? - ? ? <	1 3 5 7 9

Data found in research literature, articles, news reports, and information on company websites are implemented into Table 2 (Engel & Macht, 2016). Even though all reviewed recycling processes run on an industrialized basis, only limited data is available. Regarding the recycling efficiency, the targets set by the companies are in accordance with the EU Directive to recycle 45% of used batteries by 2016 (2000/53/EC, 2016). Detailed information about the current recycling efficiency of the companies is not stated by the firms. Additionally, the values illustrating the CO₂ recycling saving potential are not specifically mentioned anywhere, yet are simply advertised as “efficient processes”. Comparable values are given regarding the recycling capacity for LIBs, leading to a somewhat comprehensive rating.

Unfortunately, due to the lack of currently published information, the value theory evaluation and thus a best process or even generalizable model based on Value Theory could not be obtained. The companies are currently facing constant competition in order to maintain a leading role in the global competitive market for recycling EV LIBs; therefore, the firms share limited information.

In order to evaluate and rate given industrialized recycling processes for EV LIBs in the future, data needs to be generated. Research in the area of environmental impact assessment would help to move towards a comprehensive clarification and to rate current processes.

2.3 Concept of Sustainability

Sustainability is a widely discussed term with a constantly increasing public awareness, especially concepts like climate change are gaining significance. Generally, sustainability refers to the future orientated resource usage, in an industrial context it is the premise that a product should not create any waste or cause any kind of environmental pollution (Baumgartner & Zielowski, 2007; McDonough & Braungart, 2002). It is a concept that was originally created by environmentalists in the 1980s. In general accordance, sustainability is a holistic term, which does not only focus on the environmental issues (Tullberg, 2012; Gilman, 1990), it is described as a three factorial concept influenced by the factors: environment, economy, and humans as shown in the Figure 14.

Figure 14. Systems Influencing Measuring Product Sustainability (Le et al., 2016)

Measuring product sustainability remains difficult, the most common method to measure the eco-effectiveness of a product is Cradle-to-Cradle (C2C). Instead of the traditional philosophy of “Cradle-to-Grave” and the creation of a product that is gone forever, “Cradle-to-Cradle” aims for the eco-effectiveness and the usage of industrial processes that turn materials into nutrients (Le et al., 2016).

A frequently used approach to measure sustainability’s environmental aspect of a product or a process is executed by utilizing Life Cycle Assessment (LCA). LCA addresses the environmental impact of a product or process throughout its life cycle (Baumann & Tillmann, 2004). The LCA methodology forms the basis of this research, and is described in Chapter 3 in more detail.

CHAPTER 3 – Methodology

While working on this research, the methodologies were altered to generate suitable data for the research goal. After a comprehensive literature review to gather the theoretical background, appropriate interviews were prepared, which were not performed in the end due to the unwillingness of companies to share information. The LCA methodology is examined instead, to generate results on an environmental and economical basis.

3.1 Qualitative Interviews

In order to compare the different industrialized EV LIB recycling processes and to generate knowledge about future trends within battery recycling, detailed data from recycling companies is needed.

The methodology used is an iterative process, involving email correspondence, telephone calls, and potential interviews. Initially, five recycling companies are identified through an extensive literature review, as previously discussed.

The empirical approach of this study are qualitative interviews. The goal is to conduct expert interviews with higher qualified individuals in the area of lithium battery recycling. It is desired that the interviewer always narrates everything that seems to be relevant and important to her/him. The interviewer is not interrupted during his statements and questions are only asked for better understanding. Based on the small number of recycling companies to be interviewed, the qualitative approach presents an optimal solution to achieve deeper and profound results (Marshall & Rossman, 2011;

Henrik et al., 2010; Witzel, 2000). To generate the required data, an openly held interview method should be used, supplying comprehensive answers. Openly held interviews should be carried out, making use of a standardized guide/questionnaire (Mey & Mruck, 2007). Structural-wise, the interview guide is divided into different sections. Besides general questions about the recycling processes of the interviewed companies, questions about the upcoming growth in the demand of LIBs, governmental regulations regarding LIB recycling processes and future trends are asked.

Unfortunately, all identified companies are unable to provide detailed data due to privacy issues or competitive reasons. A majority of the companies did not even answer emails or phone calls. The business trait of EV LIB recycling is strongly competitive; the companies are unwilling to share any know-how being gathered over the last few decades to protect their own expertise against competitors. An example of the interview guide sent to the recycling companies can be found in the Appendix A. All interview material, such as the recruitment email, interview guide and letter of consent were created both in English and in German language depending on the company's background.

3.2 Change of Research Method

The overall purpose of this work is to compare and contrast various processes to recycle EV LIBs. The companies are currently facing constant competition in order to maintain a leading role in the global competitive market for recycling EV LIBs; therefore, the firms share limited information. All identified companies are unable to provide detailed data due to privacy issues or competitive reasons, at this time. Since

the acquisition of detailed data regarding recycling processes for EV LIBs about future trends or the comparability of industrialized processes could not be performed by executing interviews, the methodology is changed towards a model-based approach. A life cycle orientated method (LCA) is used to examine and compare the ecological impact of the different industrialized EV LIB recycling processes by using a modeling software (Umberto NXT LCA) and to identify its environmental hotspots (i.e., process stages with the most relevant impacts). Additionally, the economical aspects of the different EV LIB recycling processes are considered, based on a comparison matrix, rating the processes based on their generated benefit.

3.3 Life Cycle Assessment of EV LIB Recycling Processes

The theoretical background for the LCA methods is mainly based on “The Hitch Hiker’s Guide to LCA”, for more detailed information about LCA, please directly refer to “The Hitch Hiker’s Guide to LCA” or ISO 14040 (Baumann & Tillmann, 2004; ISO 14040, 2006).

Originally, LCA was known as Life Cycle Analysis, but in the process of time it changed towards Life Cycle Assessment due to the negative connotation that comes with the term analysis. The term was perceived too technical and therefore the expression changed towards the more comprehensive term of “assessment” in the late 1990’s. Starting in 2000 the Organisation Internationale de Normalization first published LCA standards (ISO 14040, 2006) to assess the environmental aspects and potential impacts of a product. The LCA is defined as follows according to the ISO 14040:2006 (ISO 14040, 2006):

“LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave) [ISO 14040:2006].”

The constantly rising public-awareness of environmental protection and the impacts coming with products, have lead to the development of methods to assess these impacts. LCA is a consulting-based model to identify the resource usage and various environmental impacts in different stages of the life cycle to aid environmental decision-making. The aim is to analyze organizational operations in regards to ecological deficiencies. A LCA considers all significant input and output flows, in form of an I-P-O model, and concludes an assessment of the potential environmental impacts of a product. All stages within an entire life cycle should be considered, starting with the supply of raw materials, production/manufacturing, use and disposal/recycling of the product. Every single phase is analyzed concerning its environmental impact.

According to the ISO (ISO 14040, 2006), the LCA framework consists of four different steps and corresponding feedback loops, enabling the system to adjust its performance subsequently, as shown in Figure 15.

- Goal and Scope Definition
- Inventory Analysis
- Impact Assessment
- Interpretation

Figure 15. International Standard ISO 14040 Framework (ISO 14040, 2006)

The first step of the LCA framework is the goal and scope definition phase, during this stage the goal is determined, the product/ process and the purpose of the study are decided on. The context of the study will be set, ideally all choices and specifications are made. Within this phase the reason for carrying out the study and the addressed audience are stated (Kloepffer W. , 1997; Baumann & Tillmann, 2004; Kloepffer & Grahl, 2011). Decisions that need to be made within the definition phase are concerning the scope of the study, the choice of model, the functional unit, the impact categories, the method for impact assessment and the system boundaries.

- Options to model: Define the product/ process being investigated
- Functional Unit: Define a functional unit to which all other flows of the system are related and as a basis for calculations to be made
- Choice of impact categories and method of impact assessment: Define the environmental impacts that are taken into account
- System boundaries: Delimit system studied from surrounding environment, geographical-, time- boundaries and boundaries within technical systems are defined

Allocations are made in case a process is generating more than one output stream, and only one part is used within the systems boundaries. Allocations are leading to a narrow-minded attitude and are used if a system expansion is no longer possible step (Kloepffer W. , 1997; Baumann & Tillmann, 2004; Kloepffer & Grahl, 2011). The scope definition states the most significant characteristics and assumptions and limitations are made. This phase is mandatory and influences all upcoming decisions in the LCA and is therefore particularly relevant (Kloepffer W. , 1997; Baumann & Tillmann, 2004; Kloepffer & Grahl, 2011).

In the second step, called Life Cycle Inventory Analysis (LCI), the input/output data with regard to the system is examined. A flow model of a technical system is constructed, in which only environmentally relevant flows are considered. Main parts of the LCI are the construction of a flow model, the data collection, and the calculation of environmental loads.

- Construction of the flowchart: Construct a flow chart showing the activities of the analyzed system and interactions between these activities
- Data collection: Collect detailed set of inputs and outputs for all activities of the analyzed system
- Calculation: Calculate the amount of resource use and emissions of the system in relation to the functional unit

The inventory analysis is a descriptive model without any kind of assessment (Kloepffer, 1997; Kloepffer & Grahl, 2011; Baumann & Tillmann, 2004).

During the following Life Cycle Impact Assessment stage (LCIA), the environmental consequences are described. LCIA aims to describe the impacts of the environmental loads of the inventory analysis. During the impact assessment phase the results of the inventory analysis are translated into values for the environmental impact categories, such as the Global Warming Potential, or Human Toxicity Potential. Additional normalization-, grouping-, and weighting steps can be performed in order to improve the readability of the values, and to create more environmentally relevant and comparable values. Figure 16 is summarizing the elements of the LCIA phase: Impact category definition, classification, characterization, normalization, grouping, weighting, and data quality analysis (Kloepffer, 1997; Kloepffer & Grahl, 2011; Baumann & Tillmann, 2004).

Figure 16. Elements of the LCIA phase (ISO 14040, 2006)

- Impact category definition: Specification of environmental impacts
- Classification: Sorting and assigning the LCI results to the various impact categories
- Characterization: LCI results are added up based on equivalency factors to calculate the extent of environmental impacts
- Normalization: Results are related to the actual scale for each category, to gain a better awareness of the scale of the environmental impact
- Grouping: Defines the sorting of the characterization results into one or more sets
- Weighting: Defines the relative importance of the environmental impacts by using weighting factors for the different impact categories

The calculated results from the characterization step are not comparable due to the different units of the impact categories (i.e., CO₂eq, 1,4-DCBeq). In order to compare impact categories a normalization step is carried out, based on a reference value (i.e., impact on one person in one year). The reference value “one person in one year” classifies values in terms of person equivalents (PE), or more specifically the impact potential on one person per year without stating a specific reference region (Zbicinski, 2006).

To simplify the LCIA process, read-made LCIA methods (software) can be used, in which the impact assessment procedure is included. The ready-made methods are using characterization indicators or indexes for the environmental information, so that an in-depth procedure is not necessary. These methods help to transform inventory data to total flow values of the defined impact categories. Each of the available LCIA methods have their specific measurement principle. Most common methods are ReCiPe, Ecoindicator'99, EPS, Environmental themes and EDIP (Baumann & Tillmann, 2004; Kloepffer, 1997; Kloepffer & Grahl, 2011).

The life cycle interpretation phase is the final stage of the LCA framework, in which the results of the LCI and LCIA are assessed in order to draw conclusion. These results are the basis for further conclusions, recommendations and decision-making in relation with the set scope and goal of the study. The interpretation should include the identification of important issues in relation to the results of the LCI and LCIA stages of the LCA (Baumann & Tillmann, 2004; Kloepffer, 1997; Kloepffer & Grahl, 2011).

The acquisition of environmental impact data of the examined processes is the most important step within the LCA. Apart from the literature, appropriate software is

necessary to support the assessment of environmental impacts. For the LCA, the ISO standards 14040-14043 are followed and LCA software Umberto is utilized where necessary.

The LCA methodology is conducted to assess the ecological impact of the current industrialized recycling processes. Each of the processes is modeled to determine the environmental impact and economical benefit, in order to identify the process with the lowest environmental influence and economical value.

The comparison of the economical aspects of the different industrialized EV LIB recycling processes is discussed in Section 3.4.

3.3.1 Select Environmental Indicators and Characterization Method

To identify the indicators for sustainability, the scope of this paper is limited to the environmental and economical dimension of sustainability. The environmental impact is the most significant dimension of sustainability, and well discussed in the literature. The two main components discussed are: natural resources and pollution (Freeman III et al., 2014; Rothman, 2000).

Natural resources address the use of energy, water and raw materials, as well as the waste creation created during processes. Pollution considers the contribution of processes towards global warming. While performing LCA various impact categories are used, summarized in the Table 3.

Table 3. Indicators for Sustainability

Dimension	Theme	Indicator	Unit
Environment	Natural Resources	Material Use	kg
		Energy Use	kWh
		Water Consumption	m ³
		Waste Creation	kg
	Pollution	Global Warming Potential	kg CO ₂
		Acidification Potential	kg SO ₂
		Human Toxicity, Eco-Toxicity	kg 1,4-DCB

Table 3 gives a broad overview of the environmental indicators for sustainability, a more detailed description is presented. All indicators are either directly measuring the effect of natural resources or the pollution (OECD, 2014; Baumann & Tillmann, 2004).

The indicator “material use” is measuring the total consumption of non renewable resources such as minerals and fossil fuels, whereas the indicator “energy use” is measuring the total consumption of non-renewable energy resources such as coal and other fossil fluids, which is directly related to rising air pollution. The trend is to switch to renewable energy resources. “Waste creation” is an indicator measuring the amount of waste produced causing major environmental problems, such as pollution and the relief of toxic substances. The contribution of a particular gas to global warming with comparison to carbon dioxide on a relative scale is measured by the indicator “Global Warming Potential” (GWP). The GWP is calculated by measuring the amount of emissions released during a particular process and the value resulting by multiplying it with the equivalent factor relative to carbon dioxide. The indicator “acidification

potential” (AP) is measuring the contribution to the acidification of a particular gas with comparison to sulfur dioxide on a relative scale. Gases with acidification potential are affecting soil and water quality and are calculated by measuring the quantity of emission released during particular processes and the value resulting by multiplying it with the equivalent factor relative to sulfur dioxide. “Human toxicity” (HT) is describing the expected health effects of materials with the goal to reduce usage of hazardous materials. Hazardous materials are toxic and can potentially cause harm to humans, whereas the indicator “terrestrial ecotoxicity” (TET) describes the impact of toxic substances on terrestrial ecosystems. Terrestrial ecosystems refer to systems related to land or the planet earth (Brentrup et al., 2004; Baumann & Tillmann, 2004; Guinée, 2002).

LCA assesses multiple environmental impact categories, such as the Global Warming Potential (GWP), ecosystem quality, acidification, land use and resources impacts. The present paper is focusing on the LCA of recycling processes for EV LIBs.

The scope of this research is thereby limited to the EOL segment of the LCA. The recycling phase will be considered and gases influencing the Global Warming Potential (GWP), the Human Toxicity Potential (HTP), and the Terrestrial Ecotoxicity Potential (TETP) are investigated. In the end the values are assessed that contribute to those impact categories. In regards to the GWP, the corresponding emissions, including carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfurhexafluoride (SF₆) are then converted into carbon dioxide equivalents (CO₂eq). The carbon dioxide equivalent (CO₂eq) permits the different greenhouse gases to be compared relative to one unit of CO₂. CO₂eq is

measured by multiplying the emissions of the green house gases by its 100-year Global Warming Potential (Baumann & Tillmann, 2004). The impact category toxicity includes all direct toxic effects of emissions on humans (human toxicity) and eco-systems (ecotoxicity). Toxic emissions are inorganic air pollutants, such as NH_3 , SO_2 and NO_x , plant protection substances, and heavy metals (Brentrup et al., 2004). For toxicity a model is developed by Huijbregts (2001) for estimating the toxic potential. The toxic potential is therefore expressed to a relative substance of 1,4-dichlorobenzene (1,4-DCB), called 1,4-DCBequivalent (Huijbregts, 2002).

A characterization method for LCA has been selected to address indicators to different impact categories (Baumann & Tillmann, 2004). Those methods can be applied using midpoint and endpoint methods. While the midpoint results are comprehensive and assess the ecological impact at a level in cause-effect chain from the release to the endpoint, the endpoint results are concise and evaluate the ecological impact at the areas of protection (Dong & Ng, 2014; ISO 14040, 1997). In the midpoint approach the environmental interventions are represented as a set of indicators including carbon dioxide (climate change), chlorofluorocarbon (ozone depletion), nitrogen oxides (eutrophication), sulfur dioxide (acidification) (Dong & Ng, 2014). The endpoint method translates indicators of the impact categories into damage categories, such as human health, ecosystem and resource.

Widely used characterization methods are the different types of ReCiPe, which are included in major LCA software and databases, such as SimaPro or Ecoinvent (ReCiPe, 2016). These methods are based on midpoint, endpoint or a combination of both approaches (ReCiPe, 2016). ReCiPe Midpoint method uses a midpoint approach,

the primary objective is to transform the different inventory data in relation to the different characterization factors into impact indicators for the defined impact categories (Goedkoop et al., 2009; Althaus et al., 2010). In contrast to the endpoint approach, the midpoint approach includes direct impact categories, and is not describing concrete damage categories. This paper is focusing on the ReCiPe midpoint approach, due to the relatively low uncertainty (ReCiPe, 2016). Furthermore, this approach states the environmental impact in simple reference indicators such as m³, kg CO₂eq, kg SO₂eq or 1,4-Dichlorobenzene (DCB)eq.

According to this research paper the following impact categories are selected using the ReCiPe Midpoint approach:

- Global Warming Potential (GWP100) in kg CO₂eq
- Human Toxicity Potential (HTP) in kg 1,4-DCBeq
- Terrestrial Ecotoxicity Potential (TETP) in kg 1,4-DCBeq

3.3.2 Collect Life Cycle Assessment Data

To compare the different recycling processes for EV LIBs, data is needed. Numerous ways to collect data are common and explained in the following paragraph (Baumann & Tillmann, 2004).

One possibility to collect data is by infield examination of the actual process performance, thereby specific process values can be generated. Occurring issues with this collecting method are the difficulty to get access to the processes and the potential risk to measure incorrectly or collect unusable data due to a small sample size. Another way to generate data is to use database information. Data can be found in databases and

is simple to access and analyze. The downsides of this collecting method are the lack of granularity or similarity of scope, the fact that data can be dated and the financial burden to access the databases. Another possibility is to collect data from academic sources, such as literature, journals or articles, which is mostly free and accessible over the internet or in libraries. Occurring issues with this collecting method are as well the lack of granularity or similarity of scope, the fact that data can be dated and the time effort to generate corresponding values. Often comparable data is used and assumptions are made. Additionally, data can be generated by an engineering analysis. Data is produced based on design or exergy analysis. This method can be used for any process or scope and is free of charge. The downsides are the requirement of an extensive knowledge of the processes and the time effort for the data collection. Figure 17 shows the handling of data in the course of a LCA study. Apart from using infield data and data from the literature, inventory values from databases are used to calculate the results. To generate data to perform the LCAs of this paper, two approaches are perused: data from the literature, as well as data from the LCA software tool database.

Figure 17. Handling of Data in the Course of a LCA Study
(Baumann & Tillmann, 2004)

3.3.3 Select Life Cycle Assessment Software

Detailed LCAs of products and of processes have a high complexity, therefore modeling via LCA software tool can be helpful. Databases of various materials and manufacturing processes included in those software tools help users to work with generic data, whenever the collection of specific data is difficult. Databases are independent from the LCA software and are acquired by payment or without payment. The most common databases which are acquired without any payment for LCA are: The European Reference Life Cycle Database (ELCD), the National Renewable Energy Laboratory Data Base (NREL) and the New Energy Externalities Developments for Sustainability (NEEDS) (Baumann & Tillmann, 2004).

The need for user-friendly modeling software is growing with the rising amount of data, due to extensive life cycles and policy requirements for exposure environmental impact of products and of processes. An increasing amount of software solutions are available on the market now, an international survey identified at least 24 software packages (IRIS, 2000), helping to model and analyze the environmental impacts of systems. Examples of current LCA software packages based on IRIS 2000 (Baumann & Tillmann, 2004) are shown in the Table 4 on the next page. The most common LCA software tools are currently: GaBi, OpenLCA, and Umberto NXT LCA.

Table 4. LCA Software Packages (Baumann & Tillmann, 2004)

Name of software	Country of origin	Type of LCA	Type of user	Result level	Demo available
The Boustead model 4.2 (4.4)	UK	Accounting & fullblown LCA	Design engineer Environmental engineer LCA expert	Inventory & characterisation	Yes
ECO-it 1.0	Netherlands	Screening LCA	Design engineer	Weighting	Yes
EDIP 2.11 beta (3.0 beta)	Denmark	Accounting & fullblown LCA	Design engineer LCA expert	Inventory, characterisation & weighting	No
EPS 4.0 Design System (EPS2000)	Sweden	Screening & accounting LCA	Design engineer Environmental engineer LCA expert	Inventory, characterisation & weighting	Yes
GaBi3 (4)	Germany	Fullblown LCA	LCA expert	Inventory, characterisation & weighting	Yes
GEMIS (4.13)	Germany	Screening & accounting LCA	Environmental engineer LCA expert	Characterisation	Yes
JEMAI-LCA	Japan	Fullblown LCA	Design engineer LCA expert	Inventory, characterisation & weighting	?
KCL Eco 3.0 (3.01)	Finland	Screening, accounting & fullblown LCA	Design engineer Environmental engineer LCA expert	Inventory, characterisation & weighting	Yes
LCA-IT4	Sweden	Screening, accounting & fullblown LCA	Design engineer Environmental engineer LCA expert	Inventory, characterisation & weighting	Yes
PEMS 4.6	UK	Screening, accounting & fullblown LCA	LCA expert	Inventory, characterisation & weighting	Yes
REGIS 2.1 (2.2)	Switzerland	Screening & accounting LCA	Environmental engineer LCA expert	Inventory, characterisation & weighting	Yes
Sima-Pro 4.0 (5.1)	Netherlands	Screening, accounting & fullblown LCA	Design engineer Environmental engineer LCA expert	Inventory, characterisation & weighting	Yes
TEAM™ (3.0)	France	Screening, accounting & fullblown LCA	Environmental engineer LCA expert	Inventory, characterisation & weighting	Yes
Umberto 3.5 (4.1)	Germany	Accounting & fullblown LCA	Design engineer Environmental engineer LCA expert	Inventory, characterisation & weighting	Yes

The software GaBi is created by PE International and includes a database, which makes the transfer of external databases unnecessary. This software supports model environmental-, economic-, and social impacts of complex systems and allows to collect life cycle inventories data and organize it for all life cycle phases (Ormazabalet al., 2014; GaBi, 2016).

The software OpenLCA is an open source software developed by Green Delta, the software's full version is free and can be used without any restrictions. The software comes without any database; it can be adjusted individually and combined with external

inventory data. Starting the software, the according database needs to be imported and activated, only one database can be used at the same time. Most of the recommended databases by Green Delta are focusing on agriculture or renewable energy sources (Ormazabalet al., 2014; OpenLCA, 2016).

The software Umberto NXT LCA is distributed by the ifu (Institute for Environmental IT) Hamburg GmbH and is a flexible software tool for modeling, calculation, visualization and evaluation of material and energy flows. The tool analyzes and optimizes production systems, such as small production lines, but also whole manufacturing plants or companies. The entry level of Umberto NXT LCA includes the Ecoinvent-DB v3 database. Additionally, the GaBi database from the GaBi software, as described above, can be purchased and integrated as well. The software creates process models by using drag-and-drop operations, resulting in a perti-net form. Preconfigured dataset processes can be used to model various processes (Ormazabalet al., 2014; ifu Hamburg GmbH, 1998).

A final decision is made in favor of the fee-based LCA software Umberto NXT LCA, as shown in Figure 18, utilizing the ReCiPe midpoint approach to help transforming inventory data to total flow values of the defined impact categories. The main reasons are the included Ecoinvent database, providing a large variety of generic data and the fact, that the educational license used for this paper is sponsored by the Braunschweig University of Technology.

Umberto NXT LCA uses different modeling elements to set-up the desired processes. Figure 18 shows the basic layout of the software and a modeled process using different modeling elements. The right hand side of Figure 18 shows the different

elements used, such as input-, output-, and connection elements, symbolized as colored circles (i.e., yellow, green, red). In an initial step the modeling area has to be defined, depending on the different unit operations of each process. Each modeling area is based on the examined process step, and labeled as “hydrometallurgy” or “pyrometallurgy” for example. All processes of a specific unit operation are modeled within this area. Those defined areas are also the foundation of upcoming calculations, and the allocation of resulting emissions to a specific phase of the recycling process. In a subsequent step the processes are modeled based on the introduced I-P-O model for each process by using the various drag and drop elements of the software. Each process consists of a process element (blue square), indicating the actual process, and different inputs (green circles), and outputs (red circles). To connect different processes, connecting elements are used, visualized by yellow circles. All processes are connected, using black arrows, indicating the material flows within the modeled recycling processes. The initial material flow, based on the defined FU is symbolized by a purple arrow.

Figure 18. Modeling Software Umberto NXT LCA (ifu Hamburg GmbH, 1998)

3.4 Economical Assessment of EV LIB Recycling Processes

In order to compare the different recycling processes for EV LIBs on a financial basis, an economical assessment is performed, based on each processes' benefit.

The process benefit is based on the process inputs and outputs corresponding to the current market price for each material. The processes do not include occurring overhead costs of the companies, such as rent or utility bills for electricity, which are not directly related to the contrasted recycling processes, neither are costs considered regarding used equipment, or money spent for research and development, new technology, or manual labor.

To determine each processes' benefit, all system inputs and outputs are examined and multiplied with the corresponding market price. Subsequently, the inputs are subtracted from the outputs resulting in the processes' benefit, as shown in the Equation 3.

The used Equation 1 first show the initial profit calculation, in which profit (P) is calculated by subtracting costs (C) from revenue (R). In further steps, this equation is changed to calculate the processes' benefit (PB), shown by Equation 2. Therefore, revenue is expressed as output quantity (Q_o) multiplied by price (p), and cost is stated as input quantity (Q_i) multiplied by price (p). The final process benefit calculation, Equation 3, is examined by subtracting the input materials multiplied by market price from the output materials multiplied by market price (McFadden, 1978).

Profit	=	Revenue -	Cost	
P	=	R -	C	Equation 1

Process Benefit	=	Output Quantity * Price - Input Quantity * Price	
PB	=	Q_o * p - Q_i * p	Equation 2

Process Benefit	=	Output Materials * Market Price - Input Materials * Market Price	
PB	=	Q_o * p - Q_i * p	Equation 3

The material prices are generated from several financial indexes, such as InvestmentMine, OilPrice or PlasticNews. The recyclers have to consider a carbon price for generated emissions, directly impacting the processes' benefit. This international carbon price is payable for the right to emit one metric ton of CO₂eq into the atmosphere (Luckow et al., 2015). This price is either paid in form of a carbon tax or by purchasing permits to emit emissions. In-depth information about carbon pricing and CO₂ price forecasts, can be found in the 2015 Carbon Dioxide Price Forecast (Luckow et al., 2015). In order to include the price per metric ton of CO₂eq emissions into the processes' benefit, a fixed carbon price of \$55.48 per metric ton is used, suggested by the Royal DSM (The World Bank, 2016).

The calculated process benefit for each company is further on used to rate the different industrialized recycling processes for EV LIBs by using a comparison matrix.

3.5 Process Comparison Matrix for EV LIB Recycling Processes

In order to compare the different industrialized recycling processes for EV LIBs on an environmental basis, as well as on an economical foundation, a process comparison matrix is created. This matrix contrasts the sustainable aspects of the recycling processes, generated by the LCA models, as well as the process benefit of each company. Each company will be compared regarding different criteria, based on environmental and economical aspects.

Besides the processes' benefit, the person-equivalent (PE) based on the modeled LCA processes, will be considered. All examined LCAs, executed by operating Umberto NXT LCA are performed using the ReCiPe midpoint approach. Whereas the normalization step within Umberto is established for the midpoint indicators, the weighting step is not developed, using the ReCiPe approach. Therefore, the midpoint values are weighted by using person-equivalents (GaBi, 2016). In order to get a comparable value for the environmental impact of each process, the PE value of each impact category will be added together to create a weighted total PE value. To compare both criteria, the economical aspect in form of the processes' benefit and the environmental aspect in form of a weighted total PE value, a 1:1 ratio is calculated, indicating the value of each process. The higher the calculated ratio value, the superior the recycling process compared to its competitors. Besides the two mentioned criteria, ratio of benefit (economical aspect) and PE (environmental aspect), the compliance with legislations (2000/53/EC, 2016) and the recycling of lithium carbonate will be considered.

CHAPTER 4 – Model Development and Analysis of Results

Recycling of batteries is beneficial to the environment through the prevention of raw material extraction, nevertheless the actual recycling processes still have negative effects. The governmental goal is to minimize these effects to reduce the overall impact on the environment (Castillo et al., 2002).

This paper applies the LCA method consistent with the ISO 14040 (ISO 14040, 2006) series to present an eco-econ-balance of different industrialized recycling processes that treat spent LIBs. The application of LCA methodology is used to examine the environmental impacts arising from the recycling plant's operations. Thus, net emissions of greenhouse gases are identified and the three impact categories are examined: Global Warming Potential, expressed in kilograms of carbon dioxide equivalent ($\text{kg CO}_2\text{eq}$); Human Toxicity Potential, and Terrestrial Ecotoxicity Potential, both expressed in kilograms of dichlorobenzene equivalent (kg 1,4 DCBeq).

4.1 Recycling Processes

Several globally operating recycling companies disassemble and recycle LIBs, being located in Europe (i.e., Germany, France, and Switzerland), and the United States. Different combinations of unit operations (i.e., deactivation, mechanical treatment, hydrometallurgical treatment, and pyrometallurgical treatment) result in different industrialized recycling processes for each company (Hanisch et al., 2015). All industrialized recycling processes for EV LIBs differ in certain ways, that comprise a broad variety of methods, due to the fact that the continuous development of battery

systems in the area of design or materials result in the lack of a standardized industrial recycling process (Weyhe, 2012). The different industrial recycling processes of globally operating recycling companies in the area of EV LIB recycling are reviewed in a more detailed way. Those companies are frequently mentioned in the literature, journals, reports, and in the media with a recognizable influence on the global market (Gaines, 2014; Zeng et al., 2014; Espinosa et al., 2004; Vezzini, 2014; Hanisch et al., 2015). Considering those companies, a LCA for the various recycling processes is performed in order to explore the environmental impacts, and economical aspects.

4.2 Application of Life Cycle Assessment

LCA is used to analyze and assess the environmental loads and impacts of a material/ product/ process throughout its entire life cycle (i.e., raw material extraction, manufacturing, transport, use, and final disposal) (ISO 14040, 2006; Finkbeiner et al., 2006).

The goal of this paper is to assess the potential environmental impacts and economical aspects arising from the various industrialized recycling processes of spent EV LIBs. The focus of this paper is therefore on the EOL segment of the life cycle, as shown in Figure 19. LCA methodology is applied, according to the ISO 14040 standards, to various industrialized recycling processes for the treatment of EV LIB waste.

Figure 19. Focus on End-Of-Life Segment of the Life Cycle (Rowley, 2016)

The present LCA is examined at the University of Rhode Island and its purpose is to evaluate the environmental impact of industrialized recycling processes of EV LIBs and to identify its environmental hotspots (i.e., process stages with the most relevant impacts). Findings will be used to inform researchers about the GWP, the HTP, and the TETP of EV LIB recycling processes. Five different recycling processes are compared and visualized, focusing on the environmental impact during the actual recycling process within the company.

The present paper states that the assessment does not include the entire life cycle of a product, the system boundary of the processes and therefore of the LCA is based on the EOL segment, specifically on the recycling phase, as shown in Figure 20.

Figure 20. Focus on Recycling of Product Life Cycle
(Baumann & Tillmann, 2004)

The functional unit (FU) is used to set the system boundaries and is defined as one metric ton of EV LIB; all values are given in terms of this unit. The material composition of LIBs can differ, in the segment of electric mobility there are various cell materials to compose LIBs. Most common cathode materials for EV batteries are LiCoO_2 (LCO) and LiFePO_4 (LFP) focusing on lower cost inputs (Gaines, 2014). Regarding this paper, LiCoO_2 as a cathode material is used as a part of the generic battery composition, as shown in Table 5 (Xu et al., 2008; Wang et al., 2014).

Table 5 shows the different components of the used EV LIB battery composition with LiCoO_2 as the cathode material. All battery components are stated in relation to one metric ton of spent LIBs. Besides displaying the different component masses in kilograms, the values are also stated in percent. Knowledge about the used battery composition is helpful, in addition to other used sources to determine the different streams within the modeled recycling processes.

Table 5. EV LIB Composition with LiCoO₂ as Cathode Material
(Xu et al., 2008; Wang et al., 2014)

Component	Composition (mass in%)	Composition (kg/ metric ton spent LIBs)
LiCoO ₂	27.5	275
Lithium	2.0	20
Cobalt	17.5	175
Oxygen	8.0	80
Steel/ Ni	24.5	245
Steel	20.5	205
Nickel	4.0	40
Cu/ Al	14.5	145
Copper	8.0	80
Aluminum	6.5	65
Carbon	16.0	160
Electrolyte	3.5	35
Polymer	14.0	140
	100.0%	1000 kg

The systems studied, cover all recycling activities for EV LIBs for the different companies; all other upstream or downstream processes other than the actual recycling process are excluded. The systems boundaries include the basic recycling methods, such as deactivation and dismantling of the battery systems, mechanical treatment, as well as hydro- and pyro- metallurgical process steps. Systems boundaries are defined on a global level; therefore, all values are on a global average. For specific processes, generic datasets of companies from Ecoinvent are used. Depending on the available datasets, values from mainly European companies, utilizing those processes, were obtained.

Those datasets were labeled as “global average” by the Ecoinvent, even though the processes were performed in Europe for example.

The electricity used is taken from Ecoinvent and is described as “market for electricity, medium voltage”. This Ecoinvent dataset describes the electricity available on a medium voltage level as a global average (GLO). The systems water consumption is also a reference value taken from Ecoinvent and described as “process water, main supply”, indicating the water consumption on a global average (ifu Hamburg GmbH, 1998). The electricity-, and water consumption values are applicable for all examined recycling processes, and are not further stated. Additionally, only data is used that is related to the actual recycling process of an EV LIB. It excludes for example electricity used for lighting during the processes, since it is impossible to track.

The inventory analysis and the impact assessment are both conducted in the modeling software Umberto NXT LCA. Data is collected as mentioned in Chapter 3.4 by screening data from the literature/ academic sources, such as “The International Journal of Life Cycle Assessment”, “The International Journal of Life Cycle Assessment”, “Chemical Engineering Journal”, “Hydrometallurgy Journal”, “International Journal of Sustainable Manufacturing”, “Journal of Environmental Management”; various databases and data from Ecoinvent. Ecoinvent is a peer-reviewed database to provide unified and generic data of high quality, including LCI data for over 25000 processes in various fields (Ormazabalet al., 2014; ifu Hamburg GmbH, 1998). All used sources are related to the different steps of the recycling processes. The present study focuses on the treatment of LIB waste. The data for the

examined industrialized recycling processes for spent EV LIBs is predominant up-to-date in relation to research and development.

After modeling the different recycling processes for EV LIBs in an I-P-O model, and afterwards in Umberto, final flow values are calculated, based on the total flow calculation in Umberto NXT LCA. The calculated values are indicators for the previously defined impact categories. Besides total flow values for the different impact categories, values for the emitted emission in the different stages of each recycling process are calculated by the software. For each recycling processes values are calculated using the same approach.

The following pages describe the LCI, the LCIA, executed via Umberto NXT LCA, and the Interpretation phase of LCA of the five different industrialized processes for the recycling of EV LIB waste.

4.2.1 Company 1: Inventory Analysis, Impact Assessment & Interpretation

The process of Company 1 is a mechanical and hydrometallurgical process for the recycling of spent LIBs to produce lithium carbonate. The information for the examined recycling process of Company 1 is mainly from the academic literature (Gaines, 2014; Sonoc et al., 2015; Amarakoon et al., 2013; Dunn et al., 2012) and data from the Umberto Ecoinvent software. The information and literature used to set up the recycling process of Company 1 is shown in the Appendix B. The basis of every modeled recycling process is the material flow being processed. The specific battery composition is therefore the foundation for the different inputs and outputs of the system and corresponding value streams are calculated based on them. The used values are

shown in Table 6 with corresponding quantities, units, as well as literature sources, and assumptions that are made. The recycling process of Company 1 is discussed in more detail, all occurring input and output streams are examined.

Table 6. I-P-O Model Values of Company 1

INPUTS				
Flow	Quantity	Unit	Source	Assumption
Raw material inputs				
Spent LIBS	1000	kg	Functional Unit	
Soda Ash	30	kg	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011	Process data from Gaines et al., 2011
Electricity consumption				
Electricity, medium voltage (GLO)	776	kWh	Ecoinvent	Electricity on a medium voltage level; global average (GLO)
Water consumption				
Process water, main supply	150	l	Ecoinvent	Process water consumption; global average (GLO)
OUTPUTS				
Flow	Quantity	Unit	Source	Assumption
Product output				
Mixed Plastics/ Steel, to recycler	338	kg	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011	Process data adjusted to FU
Copper/ Cobalt/ Aluminum, to industry	255	kg	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011	Process data adjusted to FU
Mixed Metal Oxides and Carbons, to industry	255	kg	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011	Process data adjusted to FU
Lithium Carbonate, to industry	30	kg	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011	Process data adjusted to FU
Solid wastes				
Residue, to landfill	102	kg	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011	Disposal of inert waste to in inert landfill, Switzerland, 1995
Water, to sewer	150	l	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011	Market for wastewater, average, Switzerland, 2000
UNIT OPERATIONS				
Flow	Source		Assumption	
Mechanical treatment				
Cryogenic cooling	Ecoinvent		This activity ends with the production of liquified nitrogen by cryogenic air separation. It was assumed that this process is equivalent to the cryogenic cooling process step of Company 1.	
Shredder	Ecoinvent		This activity is shredding components from manual dismantling. It was assumed that this process is equivalent to the shredding process step of Company 1.	
Hammermill	Dunn, J. et al., 2012		Source stated the amount of energy and water needed for this specific unit operation. It was assumed, that the collected primary data was correct/ sufficient and can be used for this process.	
Shaker table	Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011		Sources stated the amount of energy needed and resulting outputs for this specific unit operation. It was assumed, that the collected primary data was correct/ sufficient and can be used for this process.	
Scrubber	Ecoinvent		This activity is filtering the emissions resulting from the shredding process. It was assumed that this process is equivalent to the scrubber process step of Company 1.	
Hydrometallurgical treatment				
Mixing Tank	Ecoinvent		This activity is mixing the emissions resulting from the shredding process. It was assumed that this process is equivalent for Company 1.	
Filter Press	Ecoinvent		This activity is filtering the circulating lithium brine in order to generate cobalt filter cake and lithium carbonate. It was assumed that these processes are equivalent for Company 1.	
Evaporator	Ecoinvent Turek et al., 2008		This activity is evaporates the circulating lithium brine in order to generate ithium carbonate in the end. It was assumed that these processes are equivalent for Company 1.	

The initial system input is the FU (1000 kg of spent LIBs) entering the process in the mechanical treatment phase, in which the batteries are cooled to about -195 °C by a cryogenic cooling process with liquid nitrogen. The electricity required for this process is presented in Sonoc et al. (2015) and stated as 60 kWh, calculated from the heat capacity of LIBs, 1011.8 J/kg/°C, multiplied by 1000 kg and 211 °C (Sonoc et al., 2015). Working with this amount of electricity, about 24 kg of liquid nitrogen are created, assuming a medium size liquid nitrogen generator is used by the company (ING. L. A. BOSCHI, 2016). Occuring emissions are not stated in the literature or by the Company itself, therefore Ecoinvent data was used. This Ecoinvent dataset describes the production of liquified nitrogen and is assumed appropriate for this process. Subsequently, the cooled batteries are shredded and sent to a hammer mill, the required electricity for those process steps is 565.2 MJ, which is equal to 157 kWh (Gaines, 2014; Sonoc et al., 2015). Additionally, about 150 l of water are added (Sonoc et al., 2015), mixed with a lithium brine, and recirculated from a downstream process step. Occurring emissions from the shredding and hammermill treatment step are treated in a scrubber and filter, no information is given in the literature concerning the resulting emissions and the handling of those emissions in the scrubber, therefore values from Ecoinvent are used. These Ecoinvent datasets described the handling of a shredder fraction from manual dismantling and the occuring emissions, therefore, those datasets are assumed appropriate for those processes.

The resulting hammermill output stream is separated into a lithium-containing solution and undissolved product fluff, containing a low density stream of plastics and steel and a high density copper-cobalt product. The undissolved product fluff is sold to

steel refiners and is about 30% of the battery feed (Amarakoon et al., 2013). The fluff itself is composed of 133.25 kg mixed plastics (35%) and 205 kg steel (65%) (Dunn et al., 2012; Amarakoon et al., 2013), which adds up to 338.25 kg. In a subsequent step, the lithium-containing solution is separated by a shaker table, creating a “copper, and cobalt product”, being sold to industry and a further processed lithium brine, visualized in Figure 21.

The “copper, and cobalt product”, and the “cobalt filter cake”, produced in the upcoming treatment steps, add up to approximately 60% of the battery feed (Amarakoon et al., 2013) and are sold to industry. Both outputs represent about 30% of the battery feed, as shown by the mass distribution in the journal article of Sonoc et al. (2015). The copper, cobalt product itself is composed of 80 kg copper, 110 kg cobalt, and 65 kg aluminum (Dunn et al., 2012), which adds up to 255 kg. The masses are calculated in relation to the battery composition of the FU. In contrast to the used journal articles (Sonoc et al., 2015; Dunn et al., 2012; Amarakoon et al., 2013), the copper, and cobalt product is consisting of a minor aluminum content of 65 kg instead of 190.6 kg (Sonoc et al., 2015). The system outputs stated by the journal article of Gaines (2014) are focusing on a different LIB battery composition compared to the FU of this paper, stated in the beginning of Section 4.2. The copper, and cobalt product resulting from the shaker table is for example composed of 190.6 kg of aluminum (Gaines, 2014), but the FU used is only consisting of 65 kg of aluminum. Therefore, the calculation of the output streams is based on the material ratio of the journal article of Dunn et al. (2012) based on the FU. As the shaker table outputs all copper and aluminum components (Dunn et al., 2012), all copper and aluminum components are recycled from the FU. In relation to the

recycled cobalt content, a partial amount is calculated based on the 30%/ 30% ratio of the copper, cobalt product (255 kg), and the cobalt filter cake (255 kg), as previously described. The partial amount adds up to 110 kg of cobalt ejected by the shaker table as a part of the copper cobalt product, leading to a final copper, cobalt product composition of 80 kg of copper, 110 kg of cobalt, and 65 kg of aluminum, visualized in Figure 21.

The electricity used for the following process steps is based on the ratio of the values presented in Dunn et al. (2012) and the value given for the electricity of the hammermill in Sonoc et al. (2015). Presented values of Dunn et al. (2012) are not used due to the dependence on either the lithium carbonate or aluminum output, differing from the FU used in this process. Therefore, the electricity ratio of the different process steps is used in relation to the electricity needed by the hammermill and shredder of 157 kWh (Sonoc et al., 2015). The calculations resulted in a predicted energy consumption of 0.6 kWh for the shaker table, 90.6 kWh for the carbon filter press and 18 kWh is predicted for the filter press. After being emitted by the shaker table, the lithium-containing solution is sent to a holding tank and subsequently to a filter press, stating the beginning of the hydrometallurgical treatment process. The resulting cobalt cake consists of metal oxides and carbons. As previously described, the cobalt filter cake sums up to about 30% of the battery feed (Amarakoon et al., 2013), which is about 255 kg, including all nickel components of the FU (40 kg), as well as the remaining cobalt share, and most of the carbon (150 kg), visualized in Figure 21. The remaining carbon is then ejected by the system in form of lithium carbonate (Li_2CO_3). The material shares of the cobalt filter cake are calculated based on the ejection of 30% of the battery feed by the filter press, as well as the information, that the remaining parts of the nickel

shares and the outstanding shares of cobalt are ejected during this stage (Dunn et al., 2012), visualized in Figure 21.

The remaining solution is further processed in an evaporator vessel, using Ecoinvent. The amount of ejected wastewater by the system adds up to about 150 l, using a preconfigured dataset from Ecoinvent, which describes the disposal of wastewater on a global average level. In relation to the energy consumption of the evaporation process step, no process related data is available online or in the literature, therefore the energy value is based on Turek et al. (2008), using a similar process, and is assumed representative for this process. The mentioned energy value in this journal article (Turek et al., 2008) is based on the evaporation of untreated brine and stated as 450 kWh/ton for low energy evaporation, visualized in Figure 21.

In a subsequent mixing tank step, 30 kg of soda ash is added to the remaining lithium brine, only if 1000 kg of spent LIBs are treated in the entire process and about 30 kg of lithium carbonate are recovered in a final filter press step (Sonoc et al., 2015). This filter press step requires about 18 kWh, as previously calculated, and ejects about 191.75 kg of residues and 30 kg of lithium carbonate (Sonoc et al., 2015). The resulting residues are based on the remaining material streams ejected by the filter press, which are landfilled. The material input of the filter press is about 131.75 kg, which results in about 30 kg of lithium carbonate, and a final material output of 101.75 kg of residues. This treatment is modeled using Ecoinvent, in which residues are landfilled and occurring emissions are examined. Landfilling of the residues hereby means the disposal of waste, in the form of remaining materials after a process by burial.

Process data is determined by using five journal articles (Sonoc et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011; Amarakoon et al., 2013), supplying all required data.

The subsequent recycling processes of the remaining companies were examined using the same approach unless otherwise instructed, by first analyzing existing literature, adjusting the used values regarding the FU, and finally creating an I-P-O model showing the various material flows. Therefore, for the following recycling processes only the input and output values in form of a table are provided, as shown in Tables 6, 9, 12, 15, and 18.

The following Figure 21 shows the I-P-O graph of the EV LIB recycling process of Company 1 previously described.

Figure 21. I-P-O Model of Company 1

The entire process is modeled in Umberto NXT LCA, by using various drag and drop elements to model the previously set-up I-P-O mode, as discussed in Section 3.3.3. All upcoming models visualized in Umberto are modeled using the same approach.

Company 1 is divided into two different phases: mechanical treatment and hydrometallurgical treatment. In the first phase mechanical treatment all mechanical processes such as shredding, processing in a hammermill and separation by a shaker table are taking place. Additionally, the incoming battery waste is cooled down in a cryogenic cooling step before getting shredded. Occurring emissions are filtered by a scrubber afterwards. The processes in the mechanical treatment phase are located within a dark blue modeling area as shown in Figure 22.

As previously described most processes are modeled based on generic data. Preconfigured processes from Ecoinvent are used, due to the limited amount of primary data available. The shredding treatment used in this recycling process for example, is a dataset from a Swiss company, shredding electric waste after manual dismantling. This Ecoinvent dataset, as well as all other used datasets, is labeled as “global average” in Ecoinvent. To connect different processes within the software, connecting elements are needed, symbolized by yellow circles. The outputs of each process are either ejected from the system or transferred to the next unit step, and therefore further processed. After being mechanically treated, the remaining materials are undergoing hydrometallurgical treatment, located within a light blue modeling area as shown in Figure 22. The hydrometallurgical treatment step basically consists of two filtration steps, an evaporation step and a mixing tank procedure, in which lithium brine is mixed together with soda ash, in order to extract lithium carbonate as a final output.

The systems overall output consists of different valuable materials, such as copper, cobalt, aluminum, and nickel and a minor amount of lithium carbonate in a high purity (97%). Besides that, wastewater and emissions are ejected from the system. All valuable system outputs are not further investigated due to the fact, that those outputs are beyond the model boundaries. The data entry for each process step is based on the collected data as previously discussed and generic data from Ecoinvent. The generic data used matches the characteristics of the processes used for the LCA of Company 1. The final LCA of the recycling process of Company 1, modeled in Umberto NXT LCA, is shown in Figure 22.

After modeling the different recycling processes for EV LIBs in Umberto, final flow values are calculated, based on the total flow calculation in Umberto NXT LCA.

The contribution of the three indicators on the environment regarding LIB recycling of Company 1 are shown in Figure 23 and Table 7. The LCIA results of the recycling of 1000 kg of spent LIBs show, that the overall global warming potential of the process sums up to 518.84 kg CO₂eq. The impact potential for human toxicity potential is 68.98 kg 1,4-DCBeq and the ecotoxicity potential is 0.22 kg 1,4-DCBeq.

Figure 23. Company 1: Environmental Impact of Impact Categories

Table 7. Company 1: Contribution of each Phase to the Environment

Indicator	Mechanical Treatment	Hydrometallurgical Treatment	Total	Total (PE)
GWP 100 (kg CO ₂ -eq)	210.80 kg / 40.6%	308.04 kg / 59.4%	518.84 kg / 100%	2.17E-10
HTP (kg 1,4-DCB-eq)	31.10 kg / 45.1%	37.88 kg / 54.9%	68.98 kg / 100%	2.88E-11
TETP (kg 1,4-DCB-eq)	0.07 kg / 31.8%	0.15 kg / 68.2%	0.22 kg / 100%	9.20E-14

Contrasting all environmental indicators hydrometallurgy accounts for over 54% of the impacts of the LCA analysis. Table 8 on the next page presents the different emissions produced by the various process steps. All hydrometallurgical process steps require about 560 kWh of energy, especially during the evaporation step about 81% (450 kWh) of the electricity is needed. Additionally, the landfill of the resulting residues is causing most of the emissions (GWP 100: 243.5 kg CO₂eq; HTP: 33.2 kg 1,4-DCBeq; TETP: 0.15 kg 1,4-DCBeq), ejected during the hydrometallurgical treatment phase.

During the mechanical treatment phase, the battery scrap is cooled down, shredded, and sorted. Those processes require high energy input (157 kWh) and especially the shredder process is producing emissions, which are partly treated by the following scrubber. Hotspots concerning the environmental impact within the mechanical treatment phase are the electricity used by all processes, as well as the cryogenic cooling process and the treatment step of shredder fraction after manual dismantling. The overall biggest impact on the environment is caused by landfilling the residues (GWP 100: 243.5 kg CO₂eq; HTP: 33.2 kg 1,4-DCBeq; TETP: 0.15 kg 1,4-DCBeq) within the hydrometallurgical treatment phase, where the remaining materials are buried.

Table 8. Company 1: Emissions produced by Process Steps

Process Step	GWP100 (kg CO ₂ eq)	HTP (kg 1,4-DCBeq)	TETP (kg 1,4-DCBeq)
Electricity	89.5	6.1	0.004
Cryogenic Cooling	108.8	3.1	0.002
Shredding Emissions	76.8	26.2	0.07
Landfilling Residues	243.5	33.3	0.15
Disposal Wastewater	0.1	0.1	0.00
Rest	0.1	0.1	0.00
Total	518.8	68.9	0.22

The person-equivalent (PE) creates comparable values for all examined impact categories. All examined LCAs, executed by operating Umberto NXT LCA are performed using the ReCiPe midpoint approach. Whereas the normalization step within Umberto is established for the midpoint indicators, the weighting step is not developed, using the ReCiPe approach. Therefore, the midpoint values are weighted by using person-equivalents (GaBi, 2016). For the normalization step, the ‘World, Year 2000’ factors were used (ReCiPe, 2016). This provides the outcomes in terms of person equivalents (PE), or the impact per person per year, without defining a specific region, as shown in Table 7.

Figure 24 on the next page shows the results after performing the normalization step based on person equivalents (PE), indicating the effects on one person in one year. The calculated values represent comparable results of the three impact categories.

Figure 24. Company 1: Normalization of Impact Categories

The results of Figure 24 indicate, that the Global Warming Potential shows the highest impact in terms of the effects on one person in one year. Human Toxicity Potential, however, presents a lower impact when compared to the Global Warming Potential, but a higher effect on one person in one year in contrast to the Terrestrial Toxicity Potential. The higher impact of the Global Warming Potential is most likely due to the previously discussed landfilling of residues highly emitting greenhouse gases. A total PE value for all three impact categories of the recycling process of Company 1 result in about $2.5\text{E-}10$ PE. This value will be used in a subsequent process comparison step, discussed in Chapter 5.

All inventory data is generated through secondary sources without access to the actual process and might not fully represent the actual environmental effect of the recycling process of Company 1.

4.2.2 Company 2: Inventory Analysis, Impact Assessment & Interpretation

The process of Company 2 is a mechanical and hydrometallurgical process for the recycling of spent LIBs to produce lithium carbonate.

Table 9. I-P-O Model Values of Company 2

INPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Raw material inputs</i>				
Spent LIBs	1000	kg	Functional Unit	
Reagent	25	kg	Ecoinvent, Defra, 2006	Generic inorganic chemicals; global average (GLO), 2000
<i>Electricity consumption</i>				
Electricity, medium voltage (GLO)	182	kWh	Ecoinvent, Defra, 2006	Electricity on a medium voltage level; global average (GLO)
<i>Water consumption</i>				
Process water, main supply	720	l	Ecoinvent, Defra, 2006	Process water consumption; global average (GLO)
Sulfuric Acid	126	l	Ecoinvent, Defra, 2006	Primary process value (Defra, 2006); Sulfuric Acid, 2000
Lime	116	kg	Ecoinvent, Defra, 2006	Primary process value (Defra, 2006); Lime, 2000
OUTPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Product output</i>				
Cobalt salt, to cobalt producer	340	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Lithium salt, to lithium producer	198	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Iron and steel, to steel industry	245	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Non-ferrous metals, to reprocessor	65	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Copper, to reprocessor	80	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Paper and plastic, to refining	140	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
<i>Solid wastes</i>				
Gypsum, to landfill	339	kg	Ecoinvent, Defra, 2006	Disposal of gypsum to in inert landfill, Switzerland, 1995
Residue, to landfill	202	kg	Ecoinvent, Defra, 2006	Disposal of inert waste to in inert landfill, Switzerland, 1995
Water, to sewer	337	kg	Ecoinvent, Defra, 2006	Market for wastewater, average, Switzerland, 2000

Data for this process is obtained from Company 2, given by the Environmental Resources Management (Defra, 2006), representing recycling activities during 2004. Table 9 details the inputs and outputs for the LIB recycling process. The data is

confirmed by Company 2 (Defra, 2006) and approved to be representative for the recycling of one metric ton of LIBs. The used values are shown in Table 9 with corresponding quantities, units, as well as literature sources, and assumptions that are made.

The battery scrap is first treated by crushing, magnetic separation, and density separation to produce a fine powder, which is then fed to a hydrometallurgical process, involving hydrolysis, leaching, precipitation steps (Saloojee & Lloyd, 2015). The batteries are crushed in a two-step process, being processed in a rotary shredder. The crusher operates in an inert gas atmosphere (Tedjar & Foudraz, 2010). The crushed batteries are then fed to a physical separation process and separated by screening, magnetic separation, and densimetric separation. Vibrating screens of different sizes are used, the cobalt-rich fraction is sent to the hydrometallurgical treatment process and the steel and copper rich fraction is sold (Tedjar & Foudraz, 2010). The fine fraction from the physical separation process is treated by hydrolysis and suspended in stirred water. A solution of lithium hydroxide is added, in which lithium from the electrodes dissolves to produce lithium salts (Tedjar & Foudraz, 2010). The lithium-containing solution is processed in a lithium precipitation step to form lithium carbonate, using carbon dioxide from the crushing stage.

Suspended solids from the hydrolysis step are leached in a sulfuric acid, leaving carbon in the residue (Tedjar & Foudraz, 2010). The leach is further on filtered and the solution is purified previous to cobalt precipitation. Cobalt can be recovered either by electrolysis or by precipitation (Tedjar & Foudraz, 2010). The steps involved in Company 2's process are shown in following Figure 25.

The information used for the modeled recycling process of Company 2 is mainly from the academic literature and data from Ecoinvent. The information used to set up the recycling process of Company 2 is shown in the Appendix B.

Figure 25. I-P-O Model of Company 2

The basis of every modeled recycling process is the material flow being processed. The specific battery composition is therefore the foundation for the different inputs and outputs of the system and corresponding value streams are calculated based on them. As previously mentioned, the battery composition of LIBs can vary depending on the materials used, especially cathode materials. In order to generate comparable results, the same functional unit (FU) and therefore the same battery composition for EV LIBs has to be considered.

Reviewing the given values (Defra, 2006) and taking the actual battery composition of this paper (FU) into consideration, comparable (to other modeled processes) process values are identified. All unit operations and corresponding values are assumed the same way, unless otherwise instructed. The process values given by the Environmental Resources Management (Defra, 2006) are for example stating a recovered lithium amount of 30 kg and a cobalt amount of 180 kg, whereas the battery composition being introduced in the beginning of Section 4.2 only holds a maximum amount of 20 kg of lithium and 175 kg of cobalt. Therefore, all values are modified based on the FU. Additionally, for modeling the recycling process of Company 2 medium voltage electricity on a global average is used, in order to maintain comparable values, instead of using grid electricity in France as considered by Environmental Resources Management (Defra, 2006). The final values used, considering Company data from the Environmental Resources Management (Defra, 2006), as well as the actual battery composition of the FU, are shown in Table 9 with corresponding quantities, units, as well as literature sources and assumptions that are made.

The following Figure 25 shows the I-P-O graph of the EV LIB recycling process of Company 2 previously described.

The LCA of Company 2 modeled in Umberto is a mechanical and hydrometallurgical process for the recycling of spent LIBs to produce lithium carbonate, in which the battery scrap is first treated by crushing, magnetic separation, and density separation to produce a fine powder and then fed to a hydrometallurgical process, involving hydrolysis, leaching, precipitation steps (Saloojee & Lloyd, 2015).

The processes in the mechanical treatment phase are located within a dark blue modeling area as shown in Figure 26. After being mechanically treated the remaining materials are undergoing hydrometallurgical treatment, located within a light blue modeling area. The generic data used matches the characteristics of the processes used for the LCA of Company 2. The datasets used for the disposal processes of this recycling method for example, are datasets from a company in Switzerland (Umberto – Ecoinvent [1995]) supplying proper values for the disposal of gypsum and inert waste, being outputs of the modeled system. This Ecoinvent dataset, as well as all other used datasets, is labeled as “global average” in Ecoinvent.

The systems overall output consists of different valuable materials, such as copper, cobalt, aluminum, and nickel and a minor amount of lithium carbonate in a high purity. Besides that, wastewater, residue, and gypsum are ejected from the system.

All valuable system outputs are not further investigated due to the fact, that those outputs are beyond the model boundaries. The final LCA of the recycling process of Company 2, modeled in Umberto NXT LCA, is shown in the Figure 26.

After modeling the different recycling processes for EV LIBs in Umberto, final flow values are calculated, based on the total flow calculation in Umberto NXT LCA.

The contribution of the three indicators on the environment regarding LIB recycling of Company 2 are shown in Figure 27, and Table 10. The LCIA results of the recycling of 1000 kg of spent LIB show, that the overall global warming potential of the process amounts to 1324.93 kg CO₂eq. The impact potential for human toxicity potential is 179.42 kg 1,4-DCBeq and the ecotoxicity potential is 0.80 kg 1,4-DCBeq.

Figure 27. Company 2: Environmental Impact of Impact Categories

Table 10. Company 2: Contribution of each Phase to the Environment

Indicator	Mechanical Treatment	Hydrometallurgical Treatment	Total	Total (PE)
GWP 100 (kg CO ₂ -eq)	4.83 kg / 0.4%	1320.10 kg / 99.6%	1324.93 kg / 100%	5.54E-10
HTP (kg 1,4-DCB-eq)	0.33 kg / 0.2%	179.09 kg / 99.8%	179.42 kg / 100%	7.50E-11
TETP (kg 1,4-DCB-eq)	0.01 kg / 1.3%	0.79 kg / 98.7%	0.80 kg / 100%	3.34E-13

Contrasting all environmental indicators hydrometallurgy accounts for over 98.7% of the impacts of the LCA analysis. Less than 1.3% of all emissions account towards the mechanical treatment phase. All hydrometallurgical process steps require a sufficient amount of energy (140 kWh of 182 kWh). Table 11 on the next page presents the different emissions produced by the various process steps. The recycling process is mainly mechanical and chemical; hotspots of the process with a large impact on the environment are mostly hydrometallurgical treatment methods, involving the landfill of gypsum (GWP 100: 817.0 kg CO₂eq; HTP: 111.4 kg 1,4-DCBeq; TETP: 0.49 kg 1,4-DCBeq) and residue (GWP 100: 486.7 kg CO₂eq; HTP: 66.4 kg 1,4-DCBeq; TETP: 0.31 kg 1,4-DCBeq). Landfilling of the residues hereby means the disposal of waste after a process by burial. Gypsum is a mineral consisting of hydrated calcium sulfate, which is also buried in a final step, causing major emissions, as shown in Table 11.

The waste composition for landfilling is not stated in the inventory data, therefore, the impacts are modeled using a general landfill process.

The overall biggest impact on the environment is caused by landfilling the residues, and gypsum within the hydrometallurgical treatment phase, where the remaining materials are buried.

Table 11. Company 2: Emissions produced by Process Steps

Process Step	GWP100 (kg CO ₂ eq)	HTP (kg 1,4-DCBeq)	TETP (kg 1,4-DCBeq)
Electricity	20.9	1.4	0.00
Landfilling Gypsum	817.0	111.4	0.49
Landfilling Residues	486.7	66.4	0.31
Disposal Wastewater	0.2	0.1	0.00
Rest	0.1	0.1	0.00
Total	1324.9	179.4	0.80

Figure 28 shows the results after performing the normalization step based on person equivalents (PE), indicating the effects on one person in one year. The calculated values represent comparable results of the three impact categories.

Figure 28. Company 2: Normalization of Impact Categories

The results of Figure 28 indicate, that the Global Warming Potential shows the highest impact in terms of the effects on one person in one year. Human Toxicity Potential, however, presents a lower impact when compared to the Global Warming Potential, but a higher effect on one person in one year in contrast to the Terrestrial Toxicity Potential. The higher impact of the Global Warming Potential is most likely due to the previously discussed landfilling of residues, and gypsum highly emitting greenhouse gases. A total PE value for all three impact categories of the recycling process of Company 2 result in about $6.3\text{E}-10$ PE. This value will be used in a subsequent process comparison step, discussed in Chapter 5.

All inventory data is generated through secondary sources without access to the actual process and might not fully represent the actual environmental effect of the recycling process of Company 2.

4.2.3 Company 3: Inventory Analysis, Impact Assessment & Interpretation

The upcoming process of Company 3 is a mechanical and pyrometallurgical process for the recycling of spent LIBs, in which the battery scrap is first treated by crushing, and neutralization, in order to feed a pyrometallurgical process, involving leaching, a pyrolysis step (Zenger, Krebs, & Van Deutekom, 2003).

Data available about the recycling process of Company 3 is inconsistent about whether the company is using hydrometallurgical or pyrometallurgical process steps to recover materials.

Table 12. I-P-O Model Values of Company 3

INPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Raw material inputs</i>				
Spent LIBs	1000	kg	Functional Unit	
Sodium Hydroxide	350	kg	Ecoinvent, Defra, 2006	Generic inorganic chemicals; global average (GLO), 2000
<i>Electricity consumption</i>				
Electricity, medium voltage (GLO)	800	kWh	Ecoinvent, Defra, 2006	Electricity on a medium voltage level; global average (GLO)
<i>Water consumption</i>				
Process water, main supply	1,000	l	Ecoinvent, Defra, 2006	Process water consumption; global average (GLO)
OUTPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Product output</i>				
Steel/ Nickel, to steel/ nickel industry	245	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Co-Powder, to cobalt industry	200	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Non ferrous metals, to metal industry	240	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
Lithium powder, to industry	10	kg	Ecoinvent, Defra, 2006	Process data adjusted to FU
<i>Solid wastes</i>				
Plastics, to incinerator	140	kg	Ecoinvent, Defra, 2006	Market for incineration (waste), Switzerland, 1995
Residue, to landfill	275	kg	Ecoinvent, Defra, 2006	Disposal of inert waste to in inert landfill, Switzerland, 1995
Water, to sewer	1000	l	Ecoinvent, Defra, 2006	Market for wastewater, average, Switzerland, 2000
Sulfur Dioxide	40	kg	Defra, 2006	Primary process value (Defra, 2006); Sulfur Dioxide, 2000
Chlorine	40	kg	Defra, 2006	Primary process value (Defra, 2006); Chlorine, 2000

The data used, provided by Company 3 (Defra, 2006), is based on pyrometallurgical process steps, therefore, the recycling process of Company 3 is assumed representative for a pyrometallurgical process. The used values are shown in Table 12 with corresponding quantities, units, as well as literature sources, and assumptions that are made.

The spent LIBs are processed in a gaseous environment made up of carbon dioxide and fed into a shredder where the battery scrap is mechanically dismantled. During this process step, the protective atmosphere is preserved by continuously adding CO₂ (Zenger, Krebs, & Van Deutekom, 2003). When the disassembly step is completed,

moist air is inserted to the protective atmosphere to enable neutralization of the processed material. After completing this neutralization step, the protective environment is treated in a gas scrubber to reduce emissions from the process (Zenger, Krebs, & Van Deutekom, 2003). Following this process step, the scrap material is leached and washed in a sodium hydroxide solution, resulting in a solid fraction, and leaching liquor. The metal fraction is separated from the liquid and treated to remove impurities. In a final step pyrolysis is used, and subsequently an appropriate disposal of the residuals is taking place (Zenger, Krebs, & Van Deutekom, 2003).

The information used for the modeled recycling process of Company 3 is mainly from the literature, and from the Ecoinvent database. The information used to set up the recycling process of Company 3 is shown in the Appendix B.

Data for this process is obtained from Company 3, given by the Environmental Resources Management (Defra, 2006), representing recycling activities during 2004. Table 12 details the inputs and outputs for the LIB recycling process. The data is confirmed by Company 3 (Defra, 2006) and approved to be representative for the recycling of one metric ton of LIB.

The basis of every modeled recycling process is the material flow being processed. The specific battery composition is therefore the foundation for the different inputs and outputs of the system and corresponding value streams are calculated based on them.

Reviewing the given values (Defra, 2006) and taking the actual battery composition of this paper (FU) into consideration (Section 4.2), comparable process

values are identified. All unit operations and corresponding values are assumed the same way, unless otherwise instructed. The process values given by the Environmental Resources Management (Defra, 2006) are for example stating the recovery of manganese dioxide, whereas recycling the used FU of Section 4.2, no manganese is included in the battery composition and therefore, the recycling of lithium is assumed instead, being the cathode material.

Additionally, for modeling the recycling process of Company 3 medium voltage electricity on a global average is used, in order to maintain comparable values, instead of using grid electricity in Switzerland as considered by the Environmental Resources Management (Defra, 2006). The final used values, considering company data from the Environmental Resources Management (Defra, 2006), as well as the actual battery composition of the FU, are shown in Table 12 with corresponding quantities, units, as well as literature sources and assumptions that are made.

The following Figure 29 shows the I-P-O graph of the EV LIB recycling process of Company 3 previously described.

Figure 29. I-P-O Model of Company 3

The LCA of Company 3 modeled in Umberto is a mechanical and pyrometallurgical process for the recycling of spent LIBs, in which the battery scrap is

first treated by crushing, and neutralization, in order to feed a subsequent pyrometallurgical process, involving leaching, a pyrolysis step (Zenger, Krebs, & Van Deutekom, 2003).

The processes in the mechanical treatment phase are located within a dark blue modeling area as shown in Figure 30. After being mechanically treated, the remaining materials are undergoing pyrometallurgical treatment methods, located within a light blue modeling area. Preconfigured processes from Ecoinvent are used, based on primary values from Company 3 (Defra, 2006). The data entry for each process step is based on the collected data as previously discussed and generic data from Ecoinvent. The generic data used, matches the characteristics of the processes used for the LCA of Company 3. The dataset used for the incineration process of plastics for example, is from a company in Switzerland (Umberto – Ecoinvent [1995]) supplying proper values for the incineration of plastics. This Ecoinvent dataset, as well as all other used datasets, is labeled as “global average” in Ecoinvent.

The systems overall output consists of different valuable materials, such as copper, cobalt, aluminum, and nickel and a minor amount of lithium powder. Besides that, wastewater and residues are ejected from the system. All valuable system outputs are not further investigated due to the fact, that those outputs are beyond the model boundaries. The final LCA of the recycling process of Company 3, modeled in Umberto NXT LCA, is shown in the Figure 30.

Figure 30. Umberto NXT LCA Model Company 3

After modeling the different recycling processes for EV LIBs in Umberto, final flow values are calculated, based on the total flow calculation in Umberto NXT LCA.

The contribution of the three indicators on the environment regarding LIB recycling of Company 3 are shown in Figure 31, and Table 13. The LCIA results of the recycling of 1000 kg of spent LIB show, that the overall global warming potential of the process amounts to 1122.23 kg CO₂eq. The impact potential for human toxicity potential is 110.68 kg 1,4-DCBeq and the the ecotoxicity potential is 0.31 kg 1,4-DCBeq.

Figure 31. Company 3: Environmental Impact of Impact Categories

Table 13. Company 3: Contribution of each Phase to the Environment

Indicator	Mechanical Treatment	Pyrometallurgical Treatment	Total	Total (PE)
GWP 100 (kg CO ₂ -eq)	18.47 kg / 1.7%	1103.76 kg / 98.3%	1122.23 kg / 100%	4.69E-10
HTP (kg 1,4-DCB-eq)	1.26 kg / 1.1%	109.42 kg / 98.9%	110.68 kg / 100%	4.63E-11
TETP (kg 1,4-DCB-eq)	0.001 kg / 0.2%	0.31 kg / 99.8%	0.31 kg / 100%	1.32E-13

Contrasting all environmental indicators pyrometallurgy accounts for over 98.3% of the impacts of the LCA analysis. Table 14 on the next page presents the different emissions produced by the various process steps. All pyrometallurgical process steps require a sufficient amount of energy (688 kWh of 800 kWh) and have a large impact on the environment, involving the incineration of plastics (GWP 100: 541.97 kg CO₂eq; HTP: 37.74 kg 1,4-DCBeq; TETP: 0.02 kg 1,4-DCBeq) and landfill of residue (GWP 100: 486.7 kg CO₂eq; HTP: 66.4 kg 1,4-DCBeq; TETP: 0.31 kg 1,4-DCBeq). During the mechanical treatment phase, the battery scrap is shredded, and sorted, the required energy consumption is about 112 kWh.

Hotspots of the recycling process of Company 3 are the electricity generation, incineration of plastics and the landfill of residues with the largest impact overall. Burning of plastics contributed most to the Global Warming Potential. The effects of electricity generation can vary depending on the source or origin, these effects can be reduced by applying a larger proportion of renewable energy generation.

The overall biggest impact on the environment is caused by landfilling the residues, and the incineration of plastics within the pyrometallurgical treatment phase, where the remaining materials are buried or burnt.

Table 14. Company 3: Emissions produced by Process Steps

Process Step	GWP100 (kg CO ₂ eq)	HTP (kg 1,4-DCBeq)	TETP (kg 1,4-DCBeq)
Electricity	91.9	6.2	0.00
Incineration of Plastics	542.0	37.4	0.00
Landfilling Residues	486.7	66.4	0.31
Disposal Wastewater	0.2	0.1	0.00
Rest	1.3	0.5	0.00
Total	1122.2	110.7	0.31

Figure 32 shows the results after performing the normalization step based on person equivalents (PE), indicating the effects on one person in one year. The calculated values represent comparable results of the three impact categories.

Figure 32. Company 3: Normalization of Impact Categories

The results of Figure 32 indicate, that the Global Warming Potential shows the highest impact in terms of the effects on one person in one year. Human Toxicity Potential, however, presents a lower impact when compared to the Global Warming Potential, but a higher effect on one person in one year in contrast to the Terrestrial Toxicity Potential. The higher impact of the Global Warming Potential is most likely due to the previously discussed landfilling of residues, and the incineration of plastics highly emitting greenhouse gases. A total PE value for all three impact categories of the recycling process of Company 3 result in about $5.2\text{E-}10$ PE. This value will be used in a subsequent process comparison step, discussed in Chapter 5.

All inventory data is generated through secondary sources without access to the actual process and might not fully represent the actual environmental effect of the recycling process of Company 3.

4.2.4 Company 4: Inventory Analysis, Impact Assessment & Interpretation

The upcoming process of Company 4 is a pyrometallurgical treatment method for the recycling of spent LIBs, in which battery scrap is first treated in a single shaft furnace, involving preheating, pyrolysis, and smelting (Vadenbo, 2009; Cheret & Santen, 2007; Gaines et al., 2011). The used values are shown in Table 15 with corresponding quantities, units, as well as literature sources, and assumptions that are made.

Table 15. I-P-O Model Values of Company 4

INPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Raw material inputs</i>				
Spent LIBs	1000	kg	Functional Unit	
Slagformers	166	kg	Cheret et al. 2007	Primary values from company, in U.S. Patent 7169206, adjusted to FU (1000 kg)
Sand (SiO ₂)	91	kg	Cheret et al. 2007	Primary values from company, in U.S. Patent 7169206, adjusted to FU (1000 kg)
Limestone (CaO)	83	kg	Cheret et al. 2007	Primary values from company, in U.S. Patent 7169206, adjusted to FU (1000 kg)
Coke	333	kg	Cheret et al. 2007	Primary values from company, in U.S. Patent 7169206, adjusted to FU (1000 kg)
<i>Electricity consumption</i>				
Electricity, medium voltage (GLO)	1,667	kWh	Ecoinvent; Dewulf et al. 2009; Dunn et al. 2014	Electricity on a medium voltage level; global average (GLO)
<i>Water/ Air consumption</i>				
Water vapor, main supply	6110	kg	Ecoinvent; Dewulf et al. 2009; Dunn et al. 2014	Process water consumption; global average (GLO)
Preheated air of 400°C	1,042	kg	Ecoinvent; Dewulf et al. 2009; Dunn et al. 2014	Smelting process Li-ion battery waste, at the Hofors plant, Sweden, comparable
OUTPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Product output</i>				
Slag, to construction or concrete industry	565	kg	Cheret et al. 2007	Primary values from company, in U.S. Patent 7169206, adjusted to FU (1000 kg)
Alloy, to industry	448	kg	Cheret et al. 2007	Primary values from company, in U.S. Patent 7169206, adjusted to FU (1000 kg)
<i>Wastes</i>				
Water, to sewer	6110	kg	Ecoinvent	Market for wastewater, average, Switzerland, 2000
Sulfuric Acid, to landfill	168	l	Ecoinvent; Defra, 2006	Primary value from company 2, Defra, 2006; comparable
Stack Gases	329	kg	Ecoinvent; Dewulf et al. 2009	Gas cleaning process li-ion battery waste, at the Hofors plant, Sweden, comparable

Within the pyrometallurgical treatment phase lithium and other metals are ending up in the produced slag, therefore no lithium can be regained in a higher purity. Slag describes a stony waste product separated from metals during smelting processes. In order to recover nickel and lithium outputs, which can be used to create new LIBs, hydrometallurgical process steps could be added onto the existing process. Those hydrometallurgical process steps are further on not considered, mainly due to the fact, that all valuable materials, especially the lithium components, remain in the ejected slag, or alloy after being pyrometallurgically processed. Further hydrometallurgical process steps of Company 4 would rather focus on the creation of new materials by adding pure

lithium from an outside supplier, than recycling the actual remaining components from the initial FU (Cheret & Santen, 2007).

The used information to model the recycling process of Company 4 is mainly from the literature, and from the Ecoinvent database. The information used to set up the recycling process of Company 4 is shown in the Appendix B. Company 4's process is a single furnace pyrometallurgical treatment method for the recycling of LIBs. The process is carried out in a shaft furnace, in which batteries, slag formers, coke, sand, and limestone are mixed together and processed, extracting slag and molten metal (Cheret & Santen, 2007). The main focus of Company 4 is the recovery of cobalt and nickel. Based on the temperature differences within the furnace step, the process can be divided into three zones. In the upper zone, the batteries are preheated by hot gases rising through the furnace, avoiding explosions from electrolyte evaporation (Cheret & Santen, 2007; Vadenbo, 2009). The battery scrap is conveyed downwards in the furnace, reaching the plastic pyrolysis zone, in which plastics are eliminated from the battery packs (Cheret & Santen, 2007). The last zone is focusing on smelting and reduction of the remaining material. The battery scrap is transformed into two fractions: slag and alloy. The slag consists of metals, carbons, and some plastics. Lithium from the smelter is also ending up in the slag in form of lithium oxide and is therefore not recovered in a higher purity. The slag can be used in construction or concrete industry (Cheret & Santen, 2007). The alloy fraction consists of residual iron, copper, cobalt, and nickel is leached with sulfuric acid in a subsequent step. Company 4 claims a 93% recovery rate for LIBs, including metals (69%), carbon (10%) and plastics (15%), but the amount of high-value materials is much smaller (Cheret & Santen, 2007). The different treatment

methods of the recycling process of Company 4 are performed in the various facilities of the company worldwide. The goal of this paper is to analyze the actual recycling process, therefore the transportation within those plants will not be considered. Data for this process is obtained from different journal articles in the literature (Cheret & Santen, 2007; Dewulf, et al., 2010) and Ecoinvent of Umberto, both being representative for the recycling of one metric ton of LIB at Company 4. Table 15 details the inputs and outputs for the LIB recycling process. The basis of every modeled recycling process is the material flow being processed. The specific battery composition is therefore the foundation for the different inputs and outputs of the system and corresponding value streams are calculated based on them. The values used from patent of Company 4 (Cheret & Santen, 2007) are based on the recycling of 1200 kg of spent LIBs, in order to generate comparable results, the material flow is reduced to the initial value of the FU, 1000 kg of spent LIBs, therefore all values are reduced by about 17.7%. The final used values, considering company data from the literature, as well as the actual battery composition of the FU, are shown in Table 15 with corresponding quantities, units, as well as literature sources and assumptions that are made.

The following Figure 33 shows the I-P-O graph of the EV LIB recycling process of Company 4 previously described.

Figure 33. I-P-O Model of Company 4

The LCA of Company 4 modeled in Umberto is a pyrometallurgical process for the recycling of spent LIBs, in which the battery scrap is first treated in a single shaft

furnace, involving preheating, pyrolysis, and smelting (Vadenbo, 2009; Cheret & Santen, 2007). The processes in the pyrometallurgical treatment method are located within a dark blue modeling area as shown in Figure 34.

Preconfigured processes from Ecoinvent are used, based on primary values from Company 4 (Cheret & Santen, 2007). The data entry for each process step is based on the collected data as previously discussed and generic data from Ecoinvent. The generic data used, matches the characteristics of the processes used for the LCA of Company 4. The used treatment step for the landfill of sulfuric acid for example, is assumed to be an underground deposit of hazardous waste from Ecoinvent, due to the acidic nature, this generic value is based on a dataset from Germany, but labeled as a “global average”.

The systems overall output consists of different valuable materials, such as copper, cobalt, aluminum, and nickel. Besides that, wastewater and residue are ejected from the system. All valuable system outputs are not further investigated due to the fact, that those outputs are beyond the model boundaries. The final LCA of the recycling process of Company 4, modeled in Umberto NXT LCA, is shown in the Figure.

Figure 34. Umberto NXT LCA Model Company 4

After modeling the different recycling processes for EV LIBs in Umberto, final flow values are calculated, based on the total flow calculation in Umberto NXT LCA.

The contribution of the three indicators on the environment regarding LIB recycling of Company 4 are shown in Figure 35, and Table 16. The LCIA results of the recycling of 1000 kg of spent LIB show, that the overall global warming potential of the process amounts to 224.25 kg CO₂eq. The impact potential for human toxicity potential is 17,31 kg 1,4-DCBeq and the ecotoxicity potential is 0.02 kg 1,4-DCBeq.

Figure 35. Company 4: Environmental Impact of Impact Categories

Table 16. Company 4: Contribution of each Phase to the Environment

Indicator	Pyrometallurgical Treatment	Total	Total (PE)
GWP 100 (kg CO ₂ -eq)	224.25	224.25	9.37E-11
HTP (kg 1,4-DCB-eq)	17.31	17.31	7.24E-12
TETP (kg 1,4-DCB-eq)	0.02	0.02	7.94E-15

Contrasting all environmental indicators hydrometallurgy accounts for all of the impacts of the LCA analysis, as Company 4 is only focusing on pyrometallurgical treatment steps. Table 17 on the next page presents the different emissions produced by the various process steps. All pyrometallurgical process steps require about 1667 kWh of energy, involving a shaft furnace smelting process and a gas cleaning process step. Hotspots of the recycling process of Company 4 are the electricity generation (GWP 100: 192.3 kg CO₂eq; HTP: 12.9 kg 1,4-DCBeq; TETP: 0.01 kg 1,4-DCBeq) and the underground deposit of sulfuric acid (GWP 100: 31.6 kg CO₂eq; HTP: 4.1 kg 1,4-DCBeq; TETP: 0.01 kg 1,4-DCBeq) with a large impact. The effects of electricity generation can vary depending on the source or origin, these effects can be reduced by applying a larger proportion of renewable energy generation. The environmental impact resulting from the recycling process of Company 4 is comparably small in contrast to the previously examined recycling processes, due to the condensed treatment methods. Company 4 is rather focusing on the recycling of valuable materials, than on the final recovery of lithium. Lithium is remaining in the slag, which is sold for a lower price to industry. All other remaining material outputs are further treated in different companies or sold.

The only environmental effecting system outputs are the hazardous waste of used sulfuric acid, the electricity generation, and the disposal of wastewater.

Table 17. Company 4: Emissions produced by Process Steps

Process Step	GWP100 (kg CO ₂ eq)	HTP (kg 1,4-DCBeq)	TETP (kg 1,4-DCBeq)
Electricity	192.3	12.9	0.01
Landfilling Residues	31.6	4.1	0.01
Disposal Wastewater	0.3	0.2	0.00
Rest	0.1	0.1	0.00
Total	224.3	17.3	0.02

Figure 36 shows the results after performing the normalization step based on person equivalents (PE), indicating the effects on one person in one year. The calculated values represent comparable results of the three impact categories.

Figure 36. Company 4: Normalization of Impact Categories

The results of Figure 36 indicate, that the Global Warming Potential shows the highest impact in terms of the effects on one person in one year. Human Toxicity Potential, however, presents a lower impact when compared to the Global Warming Potential, but a higher effect on one person in one year in contrast to the Terrestrial Toxicity Potential. The higher impact of the Global Warming Potential is most likely due to the previously discussed landfilling of residues highly emitting greenhouse gases. A total PE value for all three impact categories of the recycling process of Company 4 result in about $1.0\text{E}-10$ PE. This value will be used in a subsequent process comparison step, discussed in Chapter 5.

All inventory data is generated through secondary sources without access to the actual process and might not fully represent the actual environmental effect of the recycling process of Company 4.

4.2.5 Company 5: Inventory Analysis, Impact Assessment & Interpretation

The upcoming process of Company 5 is a mixture of various treatment methods for the recycling of spent LIBs. The battery scrap is first treated in a partly manual disassembly step, followed by vacuum thermal treatment in a retort furnace. The material is further on mechanical separated, involving vibrating screens, magnetic separators and air separation. Subsequently, the LIB scrap is undergoing another pyrometallurgical melting process, ejecting a cobalt alloy. Finally, the stream is hydrometallurgical treated, involving leaching, precipitation and filtration, resulting in the recovery of lithium carbonate, which can be used to create new LIBs (Chagnes & Swiatowska, 2015; Georgi-Maschler et al., 2012). The used values are shown in Table

15 with corresponding quantities, units, as well as literature sources, and assumptions that are made.

The used information to model the recycling process of Company 5 is mainly from the literature (Georgi-Maschler et al., 2012), and from the Ecoinvent database. The information used to set up the recycling process of Company 5 is shown in the Appendix B. The process begins with mechanical pretreatment of LIBs to remove covers and electronic fractions, resulting in single battery cells. In a second process step pyrolysis in a resistance-heated retort furnace is examined, the volatile organic electrolyte evaporates and is ejected from the process. Subsequently, the lithium cells are crushed in a hammermill and sorted by means of a vibrating screen, magnetic separation, and air separation (Chagnes & Swiatowska, 2015). The generated material fractions are: iron-nickel and aluminum fraction, electrode foil fraction, and a fine fraction. Before the fine fraction is processed into an electric arc furnace, it is agglomerated to pellets using binder and slag components. Cobalt is recovered as an alloy, after being treated by the electric arc furnace. The slag and the flue dust are further processed in a hydrometallurgical treatment step to recover lithium. The material is leached with the addition of sulfuric acid and lithium is precipitated with adding sodium carbonate to the system. Lithium carbonate with a purity higher than 99% can be generated (Chagnes & Swiatowska, 2015; Georgi-Maschler et al., 2012).

Table 18. I-P-O Model Values of Company 5

INPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Raw material inputs</i>				
Spent LIBs	1000	kg	Functional Unit	
Sand	70	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Limestone	129	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Sulfuric Acid	126	l	Ecoinvent Georgi-Maschler et al., 2012	Primary value from company 2, Defra, 2006, comparable
<i>Electricity consumption</i>				
Electricity, medium voltage (GLO)	930	kWh	Ecoinvent/ Company 1; 2 Georgi-Maschler et al., 2012	Electricity on a medium voltage level; global average (GLO)
<i>Water/ Air consumption</i>				
Process water, main supply	150	kg	Ecoinvent	Process water consumption; global average (GLO)
OUTPUTS				
Flow	Quantity	Unit	Source	Assumption
<i>Product output</i>				
Fe-Ni fraction, to industry	184	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Al fraction, to industry	25	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Electrode foil, to industry	114	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Plastic covers/ electronic fractions, to recycling	150	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Electrolyte condensate, to industry	28	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Cobalt alloy, to industry	217	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Lithium salt (as Li2CO3), to lithium producer	198	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
<i>Wastes</i>				
Water, to sewer	150	kg	Ecoinvent Georgi-Maschler et al., 2012	Market for wastewater, average, Switzerland, 2000
Sulfuric acid, to landfill	126	l	Ecoinvent Georgi-Maschler et al., 2012	Primary value from company 2, Defra, 2006, comparable
Residue, to landfill	197	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)
Electrolyte condensate, to landfill	7	kg	Ecoinvent Georgi-Maschler et al., 2012	Laboratory value from company, adjusted to FU (1000 kg)

Data for this process is mostly obtained from one journal article (Georgi-Maschler et al., 2012) and Ecoinvent of Umberto, both being representative for the recycling of one metric ton of LIB at Company 5. Table 18 details the inputs and outputs for the LIB recycling process.

The journal article primarily used (Georgi-Maschler et al., 2012), is focusing on the recycling process of Company 5 with the slight difference of using portable Li-ion

batteries. The article is created in cooperation with Company 5, all values are generated by Company 5, using the same processes and equipment/ machines as recycling EV LIBs. Therefore, all values are assumed to be corresponding values for the recycling of EV LIBs. The basis of every modeled recycling process is the material flow being processed. The specific battery composition is therefore the foundation for the different inputs and outputs of the system and corresponding value streams are calculated based on them. The used values of Company 5 (Georgi-Maschleret al., 2012) are based on the recycling of portable LIBs, therefore, the data is adjusted in relation to the actual battery composition of EV Libs. The overall copper output in the electrode foil fraction is stated to be 105.3 kg (Georgi-Maschleret al., 2012), the FU used (Section 4.2) is composed of a maximum copper amount of 80 kg. Therefore, the corresponding materials within the electrode foil fraction are adjusted and the values are decreased by 24%.

Additionally, modeling the recycling process of Company 5, medium voltage electricity on a global average is used, in order to maintain comparable values. The final used values, considering company data from the literature, as well as the actual battery composition of the FU, are shown in Table 18 with corresponding quantities, units, as well as literature sources and assumptions that are made.

The following Figure 37 shows the I-P-O graph of the EV LIB recycling process of Company 5 previously described.

Input/ Output Graph - LCA of EV LIB Recycling Process of Company 5 (transport between the processes is highlighted with an asterisk [*]/ recirculated transport between the processes is highlighted with two asterisks [**])

The LCA of Company 5 modeled in Umberto is a mixture of various treatment methods for the recycling of spent LIBs, in which battery scrap is first treated in a partly manual disassembly step, followed by vacuum thermal treatment in a retort furnace. The material is then mechanically separated, involving vibrating screens, magnetic separators and air separation. Subsequently, the LIB scrap is undergoing another pyrometallurgical melting process, ejecting a cobalt alloy. Finally, the stream is hydrometallurgically treated, involving leaching, precipitation and filtration, resulting in the recovery of lithium carbonate, which can be used to create new LIBs (Chagnes & Swiatowska, 2015; Georgi-Maschler et al., 2012).

All mechanical treatment processes of the model are located within a dark blue modeling area as shown in Figure 38. After being mechanically treated, the remaining materials are undergoing pyrometallurgical treatment method, located within a light blue modeling area. In a final hydrometallurgical process step, modeled in a grey area, lithium carbonate is recovered in the end, which can be used to create new batteries.

Preconfigured processes from Ecoinvent are used, based on laboratory values from Company 5 (Georgi-Maschler et al., 2012). The data entry for each process step is based on the collected data as previously discussed and generic data from Ecoinvent. The generic data used, matches the characteristics of the processes used for the LCA of Company 5. The used treatment step for the landfill of sulfuric acid for example, is assumed to be an underground deposit of hazardous waste from Ecoinvent, due to the acidic nature, this generic value is based on a dataset from Germany, but listed as a global average value.

The systems overall output consists of different valuable materials, such as copper, cobalt, aluminum, and nickel. Besides that, wastewater and residue are ejected from the system. All valuable system outputs are not further investigated due to the fact, that those outputs are beyond the model boundaries. The final LCA of the recycling process of Company 5, modeled in Umberto NXT LCA, is shown in the Figure 38 on the next page.

Figure 38. Umberto NXT LCA Model Company 5

After modeling the different recycling processes for EV LIBs in Umberto, final flow values are calculated, based on the total flow calculation in Umberto NXT LCA.

The contribution of the three indicators on the environment regarding LIB recycling of Company 5 are shown in Figure 39, and Table 19. The LCIA results of the recycling of 1000 kg of spent LIB show, that the overall global warming potential of the process amounts to 871.24 kg CO₂eq. The impact value for human toxicity potential is 160,17 kg 1,4-DCBeq, and the ecotoxicity potential is 0.5 kg 1,4-DCBeq.

Figure 39. Company 5: Environmental Impact of Impact Categories

Table 19. Company 5: Contribution of each Phase to the Environment

Indicator	Mechanical Treatment	Pyrometallurgical Treatment	Hydrometallurgical Treatment	Total	Total (PE)
GWP 100 (kg CO ₂ -eq)	221.05 kg / 25.4%	120.89 kg / 13.9%	529.30 kg / 60.7%	871.24 kg / 100%	3.64E-10
HTP (kg 1,4-DCB-eq)	70.29 kg / 43.9%	12.99 kg / 8.1%	76.89 kg / 48.0%	160.17 kg / 100%	6.70E-11
TETP (kg 1,4-DCB-eq)	0.18 kg / 36.0%	0.02 kg / 4.0%	0.30 kg / 60.0%	0.50 kg / 100%	2.09E-13

Contrasting all environmental indicators hydrometallurgy accounts for over 48% of the impacts of the LCA analysis, and is therefore the unit operation indicating the highest amount of emissions. Table 20 on the next page presents the different emissions produced by the various process steps. Within hydrometallurgical processes battery scrap is treated in a leaching-, a precipitation-, and a filtration- step (140 kWh of 930 kWh), resulting in lithium carbonate, and the ejection of sulfuric acid and residues. which are further on landfilled. All performed pyrometallurgical process steps require a sufficient amount of energy (591 kWh of 930 kWh), involving a vacuum thermal treatment pyrolysis process and a carbonreductive process step. The impact caused by pyrometallurgical treatment methods is comparably small, due to the fact, that all outputs are further processed and only the electricity used, and a minor amount of electrolyte condensate is affecting the environment.

Hotspots of the recycling process of Company 5 are the electricity generation (GWP 100: 107.3 kg CO₂eq; HTP: 7.2 kg 1,4-DCBeq; TETP: 0.1 kg 1,4-DCBeq) and the underground deposit of sulfuric acid (GWP 100: 55.1 kg CO₂eq; HTP: 13.3 kg 1,4-DCBeq; TETP: 0.0 kg 1,4-DCBeq), as well as the landfill of residue with the largest impact overall (GWP 100: 474.9 kg CO₂eq; HTP: 64.8 kg 1,4-DCBeq; TETP: 0.3 kg 1,4-DCBeq). The smelting process is the most energy consuming treatment step (551 kWh) within pyrometallurgy. The effects of electricity generation can vary depending on the source or origin, these effects can be reduced by applying a larger proportion of renewable energy generation. The overall biggest impact on the environment is caused by landfilling the residues within the hydrometallurgical treatment phase, where the remaining materials are buried.

Table 20. Company 5: Emissions produced by Process Steps

Process Step	GWP100 (kg CO ₂ eq)	HTP (kg 1,4-DCBeq)	TETP (kg 1,4-DCBeq)
Electricity	107.3	7.2	0.1
Shredding Emissions	198.1	68.7	0.1
Furnace Waste	35.6	6.0	0.0
Landfilling Residues	474.9	64.8	0.3
Landfilling Sulfuric Acid	55.1	13.3	0.0
Disposal Wastewater	0.1	0.1	0.0
Rest	0.1	0.1	0.0
Total	871.2	160.2	0.5

Figure 40 on the next page shows the results after performing the normalization step based on person equivalents (PE), indicating the effects on one person in one year. The calculated values represent comparable results of the three impact categories.

Figure 40. Company 5: Normalization of Impact Categories

The results of Figure 40 indicate, that the Global Warming Potential shows the highest impact in terms of the effects on one person in one year. Human Toxicity Potential, however, presents a lower impact when compared to the Global Warming Potential, but a higher effect on one person in one year in contrast to the Terrestrial Toxicity Potential. The higher impact of the Global Warming Potential is most likely due to the previously discussed landfilling of residues highly emitting greenhouse gases. A total PE value for all three impact categories of the recycling process of Company 5 result in about $4.3\text{E}-10$ PE. This value will be used in a subsequent process comparison step, discussed in Chapter 5.

All inventory data is generated through secondary sources without access to the actual process and might not fully represent the actual environmental effect of the recycling process of Company 5.

4.3 Economical Assessment of the Recycling Processes

In order to compare the different recycling processes for EV LIBs on a financial basis, an economical assessment is performed, based on each processes' benefit. The process benefit is based on the process inputs, and outputs corresponding to the current market price for each material. The processes do not include occurring overhead costs of the companies (i.e., rent, or utility bills), neither are costs considered regarding used equipment, or money spent for research and development, new technology, or manual labor. To determine each processes' benefit, all system inputs and outputs are examined and multiplied with the corresponding market price. Subsequently, the inputs are subtracted from the outputs resulting in the processes' benefit, based on the Equations 1 to 3 shown in Section 3.4.

Table 21 shows the calculation of the process benefit of Company 1, all other process benefits for the different companies are calculated using the same approach. Corresponding values can be find in the comparison matrix in Appendix C.

Table 21. Company 1: Calculation of Process Benefit

Company	Process	Material	Amount (in metric tonne)	Material Price (US\$/ metric tonne)	Source (market price - 06/28/2016)	Benefit (US\$/ metric tonne)
Company 1						
	Mechanical Treatment/ Hydrometallurgical Treatment	Copper	0.0800	4,692.10	InvestmentMine	375.37
		Aluminium	0.0650	1,591.90	InvestmentMine	103.47
		Nickel	0.0400	8,960.00	InvestmentMine	358.40
		Lithium carbonate	0.0300	6,000.00	OilPrice	180.00
		Cobalt	0.1750	23,800.00	InvestmentMine	4165.00
		Steel/ Iron	0.2050	300.00	Quandl	61.50
		Polymer	0.1333	0.000186	Plastic News	0.00
		Electricity (in kWh)	776.0000	0.33	Statista.com - Europe	256.08
		Water	0.1500	1.31	Water Cost Index - Global	0.20
		Soda ash	0.0300	25.00	ICIS	0.75
		CO2e	0.5188	55.48	The World Bank	28.79
						4957.93

To calculate the process benefit of Company 1, shown in Table 21 on the next page, all input and output materials are examined. Those materials also include the

electricity-, and water- consumption of the process, as well as a price for emitted CO₂eq, as discussed in Section 3.4 (Luckow et al., 2015). The amount in metric tonne of each material is multiplied by the current market price of the materials, resulting in a specific process benefit for each company.

After calculating the process benefits of all five recycling companies using the same approach, Figure 41 shows the final values for each process. The values range from \$3,047.6 of Company 4, which is the lowest generated benefit, up to \$6,703.9 of Company 5, being the highest amount of benefit generated. Further discussions about the calculated values of either the environmental assessment from Section 4.2 or the economical assessment from Section 4.3 are examined in the following Chapter 5.

Figure 41. Comparison of Process Benefits

The calculated process benefit for each company is further on used to rate the different industrialized recycling processes for EV LIBs by using a comparison matrix.

CHAPTER 5 – Discussion

Besides contrasting the calculated financial benefit, and the PE value for each process; aspects, such as the recycling efficiencies, the fulfillment of legislations, and the recycling of a lithium product are used to evaluate the examined recycling processes.

Therefore, a comparison matrix is created, as shown in Appendix C, comparing all analyzed recycling processes in relation to these different aspects. Table 22 shows an excerpt of the created comparison matrix for the recycling process of Company 1 and the different criteria being considered, including the financial benefit of each process, the environmental impact, the recycling efficiency, the fulfillment of legislations, the recycling of a lithium product, and a final process ratio. All aspects are discussed in more detail on the next pages for all processes.

Table 22. Extract from Comparison Matrix

Company	Benefit (US\$/ metric tonne)	Environmental Effect (Person-Equivalent)	Ratio - Profit/ PE (1:1)	Recycling Efficiency (RE)	Legislations RE = 50 % (YES/ NO)	Source	Lithium Recycling (YES/ NO)
Company 1							
	375.37	2.50E-10	1.98E+13	below 70%	YES	Directive 2006/ 66/ EU on Batteries and Accumulators and Waste Batteries and Accumulators	YES
	103.47						
	358.40						
	180.00						
	4165.00						
	61.50						
	0.00						
	256.08						
	0.20						
	0.75						
	28.79						
	4957.93	2.5E-10	1.98E+13				YES

Company 4 is excluded from the process comparison, due to the absence of a lithium product recovery as a final system output. All other companies are currently recycling lithium outputs at a high purity. Companies, which do not focus on the recovery of lithium products, are only recycling easy accessible and valuable materials,

letting lithium remain in the slag. Therefore, the environmental impact resulting from the recycling process is comparably small in contrast to other examined recycling processes. Considering the future shortage of lithium, and the fact that Company 4 is only focusing on the recovery of valuable materials with less environmental effective processes, this process has a different starting and ending position is not directly comparable to the other processes, and therefore no longer considered.

5.1 Recycling Efficiencies and Fulfillment of Legislations

Regarding the recycling efficiency, and the fulfillment of governmental regulations ([Recycling Efficiency > 50%]; 2000/53/EC, 2016) all companies are currently recycling with an efficiency above 50%, thus governmental regulations are fulfilled by all companies. All efficiencies are stated by the companies themselves, and are not detected by a central control unit, therefore, the efficiency values can vary from the actual recycling efficiencies of the processes.

Based on the given process efficiencies all companies fulfill governmental legislations with efficiencies above 50%, therefore those aspects are no comparison criteria for a final process rating.

5.2 Recycling of a Lithium Product

Considering the recycling of lithium product as a final system output, four out of the five companies are currently recycling lithium outputs in a high purity. Companies 1, 2, and 5 are recycling lithium carbonate, Company 3 is recycling a lower lithium product, whereas Company 4 is not recycling lithium at all. Companies, which

do not focus on the recovery of lithium products, are not further contrasted, as previously described.

5.3 Economic Benefit

To contrast the economical perspective of the different industrialized recycling processes, the processes' benefit was calculated by evaluating the system inputs and outputs, as discussed in Section 4.3. Company 5, using a combination of mechanical treatment, and pyro-, hydrometallurgical process steps, and Company 2, focusing on mechanical and hydrometallurgical process steps, are generating the highest amount of financial benefit, especially due to the higher amount of lithium carbonate being recovered, as shown in Figure 41 in the previous section.

5.4 Environmental Impact

To examine the environmental impact of the different industrialized recycling processes, LCAs were performed using the modeling software Umberto NXT LCA. Table 23 displays the emission hotspots of the five recycling processes discussed in Chapter 4, impacting the environment. The red circled unit operations are producing the highest amount of emissions within the recycling processes considering the three environmental impact categories. Noticeable is, that in all recycling processes landfilling of the residues is impacting the environment, causing a higher amount of emissions. Landfilling of the residues describes the disposal of waste after a process by burial.

Processes that utilize pyrometallurgical unit operations, such as temperature intensive smelting processes, tend to have a higher energy consumption, resulting in

higher emissions. This is the reason why the electricity generation of Companies 4, and 5 is higher, and has a bigger impact on the environment, compared to the other processes. Company 3 is also utilizing pyrometallurgical unit operations, but the required energy consumption is comparably low. Emissions resulting from shredding battery components are impacting the environment to different degrees depending on the presence of a subsequent scrubber, and filter step. Company 1 is filtering all occurring emissions caused by the shredding process, whereas Company 5 is emitting all gases of the shredding process without a subsequent scrubber, or filter unit operation.

In general processes that end up landfilling residues, incinerate plastics, shred battery components without a subsequent scrubber step, or utilize unit operations with a high amount of energy are tending to create the highest amount of emissions.

Table 23. Process Hotspots of Recycling Processes

Company 1	Company 2	Company 3	Company 4	Company 5
Electricity Generation	Electricity Generation	Electricity Generation	Electricity Generation	Electricity Generation
Cryogenic Cooling	Landfilling Gypsum	Landfilling Residues	Landfilling Residues	Shredding Emissions
Shredding Emissions	Landfilling Residues	Disposal Wastewater	Disposal Wastewater	Furnace Waste
Landfilling Residues	Disposal Wastewater	Incineration of Plastics		Landfilling Residues
Disposal Wastewater				Landfilling Sulfuric Acid
				Disposal Wastewater

After summarizing the processes emission hotspots, Figure 42 shows an overall comparison of the calculated environmental impact of all five different recycling processes for EV LIBs. The figure is contrasting all three defined impact categories, as

well as the comparison value expressed in person equivalents. The larger the PE value, symbolized by a grey bar in Figure 42, the greater the overall environmental impact of the process.

Contrasting all defined impact categories in relation to the examined recycling processes, different specifications of each process become noticeable, depending on the unit operations used. The final values of the impact categories are varying for each process, mainly influenced by the processes hotspots, as previously discussed. The GWP100, and the TETP of Company 2 are noticeably higher compared to all other processes, mainly due to the final landfill of residue, and gypsum impacting the environment. Especially the TETP shows a relatively high value compared to all other processes, caused due the landfill, and the direct effect of the buried waste on the soil. Besides Company 2, Company 3 is also showing a higher GWP100 value compared to Companies 1, 4, and 5. In addition to the landfill of residues, the recycling process of Company 3 is also causing a higher amount of emissions by the incineration of plastics. Company 4 is showing the lowest environmental impact with regard to all impact categories (i.e., GWP100, HTP, and TETP), but is excluded from the process comparison, due to the absence of a lithium product recovery as a final system output, the environmental impact resulting from the recycling process is comparably small in contrast to other examined recycling processes, as previously discussed.

Analyzing the environmental impact of the five different recycling processes based on the total PE value, Company 4 is producing the lowest amount of emissions, followed by Company 1, and Company 5, as visualized in Figure 42. Company 1 is focusing on mechanical-, and hydrometallurgical processes, whereas Company 5 uses a

combination of mechanical-, pyro, and hydrometallurgical treatment steps to recycle EV LIBs.

Figure 42. Overall Environmental Comparison of Recycling Processes

5.5 Comparison of Economic Benefit and Environmental Impact

After identifying the environmental- (PE), and the economic effect (US\$/ metric ton) of the different industrialized recycling processes (i.e., Companies 1, 2, 3, and 5), Figure 43 compares both aspects, showing the highest/ lowest effect on the environment, and the largest/ smallest economical benefit. From an environmental standpoint, the environmental process with the lowest impact is considered to be Company 1, as shown in Figure 43, followed by Company 5, as previously discussed. Company 3 is utilizing a combination of mechanical treatment and pyrometallurgical process steps with a final recovery of lower lithium product, but with an overall lower performance compared to the other processes. On a financial basis, Company 5, using a combination of mechanical treatment, and pyro-, hydrometallurgical process steps, and Company 2,

focusing on mechanical and hydrometallurgical process steps, are generating the highest amount of financial benefit, especially due to the higher amount of lithium carbonate being recovered.

Figure 43. Comparison based on Environmental and Economic Effects

5.6 Process Rating of the different Recycling Processes for EV LIBs

In order to finally rate the different industrialized recycling processes for EV LIBs, and after considering the various comparison aspects, the recycling processes are evaluated on an environmental, and economical basis, by calculating a ratio, indicating the value of each recycling process for EV LIBs. This ratio is based on the processes' benefit, as well as on the PE value indicating the environmental impact of each process, visualized in Figure 44.

Figure 44 shows the different ratio values of Companies 1, 2, 3, and 5; a higher calculated ratio value indicates a superior process, or rank compared to other processes. Therefore, a recycling process based on mechanical and hydrometallurgical (Company

1), or mechanical-, pyro- and hydrometallurgical process steps (Company 5) is suggested, showing the highest ratio. Detailed information about the contrasted criteria is accessible in Appendix C, showing the overall comparison matrix.

Figure 44. Ratio based on Environmental and Economical Effects

Overall, this paper suggests to utilize the recycling process of Company 1, or Company 5 on a comprehensive standpoint, contrasting both, environmental and economical aspects, with the highest ratio. Company 1 is recycling batteries based on a combination of mechanical and hydrometallurgical treatment steps with a comparably small amount of emissions and a sufficient amount of benefit, whereas Company 5 is focusing on the combination of three unit operations: mechanical treatment, including deactivation steps, pyro-, and hydrometallurgical treatment. Company 5's emissions are higher, but the generated output also creates more financial benefit, especially due to the higher amount of lithium carbonate being recovered.

CHAPTER 6 – Conclusion

6.1 Conclusions

The aim of this paper was to examine the different industrialized recycling processes that are currently used for recycling EV LIBs, and to compare these processes focusing on environmental impacts and associated economical aspects. In the beginning, LIBs were described in terms of their components, composition, and applications. The current recycling processes for the recycling of EV LIBs were then identified, and compared in relation to the processes and recovered materials. In a subsequent step, different recycling processes were compared based on evaluating the environmental effects of recycling EV LIBs by the application of the LCA methodology. Therefore, the modeling software Umberto NXT LCA was used with the ReCiPe midpoint approach. In a final stage of this paper, the industrialized recycling processes were compared on an economical basis, contrasting the processes' benefit.

By applying the LCA methodology onto the different EV LIB recycling processes, the hotspots in the different stages of the recycling processes could be identified, impacting the environment. The results generated by the LCAs of the different processes highlight that a major part of the impacts of the recycling processes are related to the landfill of material waste, the incineration of plastics and the generated electricity, especially for energy intensive processes, such as smelting treatment methods. The leading influence of hydrometallurgical processes to global warming was the effect of landfilling residues or gypsum produced during the process. In comparison, the major influence to the impact categories from the pyrometallurgical treatment

method was the incineration of plastics. Mechanical, and hydrometallurgical treatment steps are capable of recovering a higher amount of materials and use less energy than pyrometallurgical techniques. A major disadvantage of all pyrometallurgical recycling methods is the fact, that lithium carbonate can not be recovered. In terms of environmental effects, this paper identified processes that utilize low temperatures, and are capable of recovering both plastics, and lithium as most beneficial processes. From an environmental standpoint, the least environmental effective process was considered to be Company 4, using pyrometallurgical process steps, followed by Company 1, involving a combination of mechanical treatment and hydrometallurgical process steps. Company 4 was not considered due to the absence of a lithium recovery. Considering the future shortage of lithium, and the fact that Company 4 is only focusing on the recovery of valuable materials with less environmental effective processes, this process had a different starting and ending position and was not directly comparable to the other processes. A potential future legislation regarding a mandatory lithium recovery, would also pressure Company 4 to change the recycling process, resulting in higher emissions. Therefore, Company 1 is the recycling process with the smallest environmental impact, while still recycling lithium carbonate. Company 1's process is followed by the process of Company 5, using a combination of mechanical treatment, and pyro-, hydrometallurgical process steps. A recycling process based on mechanical and hydrometallurgical or pyro- and hydrometallurgical process steps is suggested, using an appropriate pre-treatment to recover as many battery components as possible.

To contrast the economical perspective of the different industrialized recycling processes a comparison matrix was created. The most commonly recovered materials

are copper, nickel, and cobalt, which are also the materials with one of the highest values per metric ton of spent LIBs. After determining the benefit of the different recycling processes, by evaluating the system inputs and outputs, the processes could be rated. Company 5, using a combination of mechanical treatment, and pyro-, hydrometallurgical process steps, and Company 2, focusing on mechanical and hydrometallurgical process steps, are generating the highest amount of benefit, especially due to the higher amount of lithium carbonate being recovered.

To compare the recycling processes simultaneously on an environmental, and economical basis a ratio (process benefit/ PE) was calculated, indicating the value of each recycling process for EV LIBs. Therefore, a recycling process based on mechanical and hydrometallurgical or mechanical-, pyro- and hydrometallurgical process steps is suggested, based on the calculated ratio and the fulfillment of a lithium recovery.

Overall, this paper suggests to utilize the recycling process of Company 1 or Company 5 on a comprehensive standpoint, contrasting both, environmental and economical aspects, with the highest calculated ratio. Company 1 is recycling batteries based on a combination of mechanical, and hydrometallurgical treatment steps with a comparably small amount of emissions, and a sufficient amount of benefit, whereas Company 5 is focusing on the combination of three unit operations: mechanical treatment, pyro-, and hydrometallurgical process steps. Company 5's emissions are higher, but the generated output also creates more benefit, especially due to the higher amount of lithium carbonate being recovered.

A future development perspective for recycling processes of EV LIBs can be given, suggesting a future increase of utilizing the recycling processes of Company 1 or

Company 5, based environmental and economical aspects. Company 1, and Company 5 are providing a reasonable amount of lithium carbonate, while using a financial efficient process on a low emission level.

This LCA study characterizes one of the few studies in this area and aims to be helpful for further research. The presented results can be relevant to policy makers, and recyclers since this type of waste is currently part of the European waste legislation for the treatment of WEEE. The knowledge gained from this study will make the recycling companies more conscious in their environmental behavior.

6.2 Limitations

Unfortunately, all identified companies only provide a minor amount of data due to privacy issues or competitive reasons. A majority of the companies did not answer emails or telephone calls. The business trait of EV LIB recycling is strongly competitive; the companies are unwilling to share know-how being gathered over the last few decades to protect their shareholders and expertise against competitors.

A major limitation of this paper was that the corresponding values used to model the recycling processes, were not directly related to the specific processes. The impacts calculated were based on lifecycle inventory data from the literature and LCA databases and subsequently predominant assumptions for the specific industrialized recycling processes.

Furthermore, this paper did not contrast the way inputs were produced or resulting outputs were processed in further steps, nor the actual environmental impact due to transportation. Concerning the modeling software used, Umberto NXT LCA is a

European software which might not consider the differences within the environmental mechanisms in the USA or other countries. The software setup can not be adjusted, therefore the characterization of emissions or the determination of indicators might be influenced.

Another limitation was the extent of variation regarding the environmental effects due to the different battery types and battery compositions (e.g. cathode materials) (Bernardes et al., 2004). Depending on the battery type recycled, the environmental effect can vary even though the same recycling processes are used.

Concerning the economical aspects for the different industrialized recycling processes, a major limitation was the way the materials were emitted by the system's. The system outputs are not emitted in a pure form; in most cases the materials are ejected in form of an alloy or a slag. This circumstance can influence the actual benefit generated by the processes, and therefore the stated benefit values are only indicating a trend. Exact material prices for different composed outcomes, such as slags, are not specifically stated online or in the literature.

6.3 Development Perspectives and Further Research

Future development of LIBs is prognosticated in the area of battery composition to improve battery performance. Research of new chemistries often does not focus on how batteries will be recycled, therefore feeding these batteries into existing recycling processes result in a reduced product value. EV LIB recycling processes tend towards a system in which different battery types have specific recycling processes, each committed to the specific chemistry.

The focus is on low temperature processes such as mechanical and hydrometallurgical processes, and on combinations of mechanical, hydrometallurgical and pyrometallurgical methods. Mechanical and hydrometallurgical treatment steps are capable of recovering a higher amount of materials and use less energy than pyrometallurgical techniques. As lithium supplies deplete, the trend is shifting from purely pyrometallurgical processes towards investing in the establishment of hydrometallurgical treatment to optimize the recycling process.

Further research can be established from this paper to assess how future LIB recycling could be examined in order to minimize the environmental impacts of recycling and how to improve the recovery of different materials. A LCA of the different industrialized recycling processes can be performed, considering all corresponding environmental loads including emissions resulting from the creation of used inputs and occurring emission due to additional recycling steps of system outputs.

New recycling processes should be designed with a stronger orientation towards a more lithium based recovery in order to counteract a future lithium shortage.

APPENDICES

Appendix A – Interview Guide

Development Perspectives of Recycling Processes for Lithium-Ion Electric Vehicle Batteries

Introduction

My name is Jan Engel, I am studying Industrial & Systems Engineering at the University of Rhode Island and I am currently working on my Master Thesis.

Within the scope of my Master Thesis at the Department of Industrial & Systems Engineering at the University of Rhode Island, I investigate the development perspectives of lithium-ion recycling processes. Hence, the reason for the requested interview.

From year to year, an enormous amount of research was conducted about battery recycling of electric vehicles. A few industrial companies are able to recycle large amounts of lithium-ion batteries for electric vehicles. Driven by a growing demand for electric vehicles, it is questionable, whether the demand can be supplied while fulfilling the current regulations. Of particular interest is the way battery recycling of lithium-ion electric vehicle batteries (EV batteries) will proceed into the future. Can the increased future demand be met with the existing recycling methods or does it tend toward the development of different methods?

During the research phase for this paper I noticed that there currently is no single generalizable approach to satisfy the rising recycling demand of lithium-ion EV batteries. Of particular interest are estimations regarding the future trends of LIB recycling processes.

With your consent I will record the interview. The primary reason for this is to maintain a naturalistic conversation while still taking adequate notes. The interviews will be transcribed and remain confidential. I will be the only person listening to the conservation material and all recorded data will be deleted after the transcription is completed. The results will be anonymized, all personal data which would allow to draw conclusions about the interviewer will be removed.

The empirical approach of this study are qualitative interviews. The goal is to conduct expert interviews with higher qualified individuals in the area of lithium battery recycling. It is desired that the interviewer always narrates everything that seems to be relevant and important to him. The interviewer is not interrupted during his statements and questions are only ask for better understanding. Please see the attached survey.

I. Short Summary – Research Topic

1. Research Topic: Development Perspectives of Recycling Processes for EV LIBs
2. This is an open run interview with focus on extensive statements regarding the research question.
3. The questions in the following section are introductory questions and not relevant for the evaluation. These questions are only to get a better insight of your daily work life.

II. Introduction

1. Would you describe your current field of operation for your company?
 - a. How long have you been currently working in this specific area?
2. Can you provide some general information about your firm?
 - a. What is your company's size/How many employees/Which is the most dominant business division (EV battery recycling?)
3. What kind of batteries are recycled at your company? Are there different plants within your company responsible for the recycling of lithium-ion batteries?
 - a. If yes, how do they differ?
 - b. Where are they located?
4. From who do you receive used batteries? Is your company currently working with any OEM's?

III. Recycling Processes

1. Can you describe the basic procedure of your company's recycling processes?
2. Can you describe the recycling process for lithium-ion EV batteries in more detail?
 - a. How does your company handle complexities such as the variety of battery design (LIBs) and compositions (battery cells [active materials])?

3. What is the most innovative aspect of your LIB recycling process?
4. What are the strengths and weaknesses of your LIB recycling process?
5. Why did your company decide to use this specific recycling process for EV LIBs?
6. From your point of view, what is the competitive advantage of your recycling process for lithium-ion EV batteries compared to competing firms?
 - a. Would you say it is superior?
 - b. If so, by how much (1 to 5 [least to most])?

IV. Rising Demand & Regulations

1. What can you tell me about the recycling capacity, recycling efficiency and CO₂ savings of your LIB EV battery recycling process?
2. How would you estimate the future rise in LIBs?
 - a. Are you able to supply the demand (regarding current capacity and potential expansions)?
3. Do you currently meet the requirements set by the 2000 EU ELV Directive to recycle 95% of used batteries?
 - a. If not, how will you try to meet those requirements?
4. Can you tell me, if your company is considering the future shortage of lithium and therefore acts towards an increased focus on lithium recycling? Or will your company pursue an approach towards a primary recycling of cobalt, nickel, copper?
 - a. Would your company be able to react to lithium based regulations, such as the recycling efficiency of lithium to a specific degree (perhaps 90% lithium recycling efficiency, to prevent future shortage)?

V. Future Outlook & Perspectives

1. Do you believe that the processes will focus more on the recycling of lithium in the future?
2. Where do you see the future of recycling LIBs? Future trends or methods?
3. Do you see a possible movement towards a more standardized recycling process?
4. What can you tell me about future trend/plans regarding recycling processes for EV LIBs in your company? Will you continue with your current processes?

VI. Final Statement

1. We have been discussing a series of arguments. I will finally summarize the most important aspects which were mentioned during this interview.
2. Is there still something you want to say, which was not mentioned yet? Something, which was not picked up? Do you have any suggestions?
3. Do you have any questions for me?

I want to thank you for your participation in this interview. If you would like to receive the results after completing the Master Thesis, please let me know.

M.S. Candidate in Systems Engineering – University of Rhode Island

Appendix B – Recycling Processes

Company 1:

Company 1	References	Content	Figures
1	Dunn, J. B., Gaines, L., Barnes, M., Wang, M., & Sullivan, J. (2012). Material and energy flows in the materials production, assembly, and end-of-life stages of the automotive lithium-ion battery life cycle (No. ANL/ESD/12-3). Argonne National Laboratory (ANL).	<p>To model this process, we obtained data from Company 1, which uses this technology in XY. The material flows in this process are listed in Table 37. All data except the soda ash input, which is assumed to be at a stoichiometric ratio, were provided by Company 1. The energy consumption of the shredder and hammermill is estimated at 0.54 mmBtu/lb material to a per-ton-Li2CO3 basis with Equation 18. Note that the fraction of active material in the streams entering and leaving these process steps are equal, so mass allocation of the energy intensity effectively multiplies the value by one. Where EIShred, Li2CO3 is the energy of the shredding and hammermill steps allocated to Li2CO3; EIShred is the energy consumption of these steps (0.54 mmBtu/lb material). In the case of aluminum, the energy intensity of the shredding and hammermill step is 0.54 mmBtu/lb aluminum. The aluminum is subsequently separated from plastics, copper, anode and cathode material, and cobalt by means of a shaker table. Energy consumption for the shaker table was estimated at 0.003 mmBtu/lb, which is the energy consumption of a belt conveyor used in a material recovery facility (Niensta and Solano-Mora 1997). This approach could underestimate the energy the shaker table consumes because it may move more than a belt conveyor.</p> <p>Returning to Li2CO3, we calculated the energy intensity of two filtration steps that precede its recovery from the process, but we considered that the energy consumption of the intermediate steps in the tanks is negligible. For the filter press, we adopted a best energy intensity value based on data in Brown et al. (1996) for filtration of high-solids streams. (The stream entering the first filter press in the Company 1 process could have a solid-to-liquid ratio of 6:1.) In the manufacture of cellulosic fibers, a stream that is 98% solids requires 0.26 mmBtu/lb to filter. Filtering a stream with 83% solids in the manufacture of synthetic rubber consumes 0.34 mmBtu/lb. In our analysis of intermediate recycling, we used a value of 0.3 mmBtu/lb for the filter press steps. For the first filter press, we applied mass allocation to yield a value of 7×10^{-4} mmBtu/lb Li2CO3. The second filter press has a single output stream of Li2CO3, so the energy burden falls fully on this product. The energy intensities for each step of the intermediate recycling process are displayed in Table 38. Note that the output Li2CO3 could be either converted to LiCoO2 by the firing step in the pyrometallurgical process or to LiMn2O4 from roasting the carbonate with Mn2O3, as described in Section 3.3.</p>	<p>The diagram illustrates the recycling process for lithium-ion batteries. It starts with 'Shredding and Hammermill' which feeds into 'Separation by Shaker Table'. This leads to 'Aluminum', 'Copper', 'Anode and Cathode Material', and 'Cobalt'. These materials then go through 'Filtering' and 'Filtration' steps, eventually leading to 'Li2CO3' and 'LiCoO2'.</p>
2	Arora, Y. (2015). Lithium-ion battery systems: a process flow and systems framework designed for use in the development of life cycle energy model.	<p>Company 1 claims to be the only company in the world that can recycle lithium-based batteries of any shape and size (Company 1, Inc., 2014). The company uses a proprietary combination of mechanical and chemical process, but Figure 19 shows the general steps taken in lithium processing, as derived from an Environmental Assessment for proposed lithium recovery in a battery recycling facility (Vadenbo, 2009). Li-ion batteries are first discharged to ensure safety and then circuits and wires are removed for recycling. The battery packs are disassembled and sent through a process of mechanical and chemical treatments to recover Li-ion fluff, copper cobalt, and cobalt filter cake (Gaines, et al., 2011). Fluff mainly consists of plastic and steel that can be used for steel recovery or disposal, depending upon the value of the steel content (Vadenbo, 2009). Lithium is extracted along with the fluff where it is mixed with sodium carbonate (Na2CO3) to produce lithium carbonate as a final product (Vadenbo, 2009). Copper cobalt product yields "salable metals" such as copper, cobalt, nickel, aluminum (Gaines, et al., 2011) at separation and recovery during their metallurgical operations (Vadenbo, 2009). Cobalt filter cake is also exposed to metallurgical operations and can be used as coating for appliances (Vadenbo, 2009).</p>	<p>The diagram shows the recycling process for lithium-ion batteries. It starts with 'Shredding and Hammermill' which feeds into 'Separation by Shaker Table'. This leads to 'Aluminum', 'Copper', 'Anode and Cathode Material', and 'Cobalt'. These materials then go through 'Filtering' and 'Filtration' steps, eventually leading to 'Li2CO3' and 'LiCoO2'.</p>
3	Lain, M. J. (2001). Recycling of lithium ion cells and batteries. Journal of power sources, 97, 736-738.	<p>In the Company 1 process [23], old batteries go into a hammer mill and are shredded, allowing components made of aluminum, copper, and steel to be separated easily. Larger batteries that might still hold a charge are cryogenically frozen with liquid nitrogen at -325 before being hammered and shredded. Lithium is then extracted by flooding the battery chambers in a caustic bath that dissolves lithium salts, which are filtered out and used to produce lithium carbonate. The remaining sludge is processed to recover cobalt, which is used to make battery electrodes.</p>	
4	Yan, J. (2015). Handbook of Clean Energy Systems, 6 Volume Set (Vol. 5). John Wiley & Sons.	<p>Company 1 uses a combination of mechanical treatment and hydrometallurgical processing for the recovery of metals from spent LIBs. Company 1 commercialized one of the first processes for the recycling of lithium batteries in 1992. The previous development was motivated by the demand for a lithium battery recycling process in military systems (Miller and McLaughlin, 2001). In this former process, liquid nitrogen was used to deactivate the batteries and to reduce the reactivity of the metallic lithium during mechanical treatment (McLaughlin and Adams, 1999). This "is based on the principle that the kinetics of typical chemical reactions is halved when the temperature is decreased by 10 degrees. Therefore, at the temperature of liquid nitrogen (-273°C) the oxidation reaction rate is only 1/250000 of the room temperature rate" (Miller and McLaughlin, 2001). In 2009, the recycling of LIBs at Company 1's plant in X was granted by the US Department of Energy (Gaines et al., 2011a). Today, the mechanical treatment (more precisely the comminution of the LIBs) is carried out with a crusher operating under a liquid solution. As a result of this, it is possible to reduce the reactivity of the processed batteries and to prevent volatile emissions. Larger battery packs (e.g., from hybrid and electric vehicles) first go through a manual disassembly process before the separated cells or smaller packs (i.e., laptop, power tool, and cell phone) are fed to the automated crusher (Company 1 Technologies, Inc., 2014). The crushing is performed by a hammer mill while the brine solution, used to accomplish a safer comminution, is recirculated from a downstream process step. Through this first mechanical process step, a so-called Li-ion fluff containing plastics and steel can be recovered. Depending on the amount of steel in this fluff, it could be disposed directly, or the steel could be recovered in a subsequent process. The next step, a mechanical separation process, is realized by a shaker table as seen in Figure 12. By injecting water and the movement of the table, two fractions can be recovered: a mixture of copper, cobalt, and aluminum and a slurry containing lithium, dispersed cobalt, and carbon. This remnant slurry is first put into a mix tank for further processing such as heating and reacting with added substances before it is transferred to a storage tank. Subsequently, the contained cobalt and carbon can be filtered out by means of a filter press. The emerging filter cake can be sold directly, or the cobalt can be recovered with higher purity through further metallurgical processing. The extracted Li-brine can either be recirculated to serve as an input for the wet crushing step or it can be transferred to a mixing tank where sodium carbonate (Na2CO3) is added. Adding Na2CO3 leads to the formation of insoluble lithium carbonate (Li2CO3) precipitating out of the solution. Afterward it can be filtered, washed, and dried (Vezzini, 2014; Vadenbo, 2009).</p>	
5	Sonoc, A., Jeswiet, J., & Soo, V. K. (2015). Opportunities to Improve Recycling of Automotive Lithium Ion Batteries. Procedia CIRP, 29, 752-757.	<p>In the Company 1 process lithium metal primary batteries and lithium ion secondary batteries are recycled. Batteries deemed to be reactive, such as lithium metal batteries and large lithium ion batteries, are cryogenically cooled with liquid nitrogen to -196 °C; at this temperature the lithium inside the cells is unreactive [17]. The batteries are then shredded and immersed in water. Lithium or metal react with the water to produce lithium hydroxide and hydrogen gas, which is burned above the solution [8]. See Fig. 2 for an overview of the whole process. The figure is the most detailed mass flow information of the process available in the open literature and the only information which can be used to calculate approximate lithium yield. The lithium composition for lithium ion batteries varies between 1.2 and 2 % [18]. If the 907.4 kg of batteries in Fig. 2 were all lithium ion batteries then the lithium yield of the Company 1 process is between 15 and 26%, determine the rate of inert gas injection. The different fractions obtained after shredding are: a fines fraction rich in metal oxides and carbon, a magnetic fraction composed of casings, a dense non-magnetic fraction made of Al and Cu current collectors, and a low density non-magnetic fraction of paper and plastic. The fractions are separated, while still under an inert atmosphere. The fines fraction is added to water. Lithium in the fines reacts with the water and releases hydrogen gas. The water is heavily stirred and the fines are added in a very controlled manner to prevent the accumulation of hydrogen gas and an explosion. To further prevent an explosion, the atmosphere above the bath is maintained oxygen poor. The water becomes rich in lithium hydroxide and lithium is recovered by adding sodium carbonate or phosphoric acid. Hydrometallurgical means are used to recover the rest of the materials. The lithium yield is unknown. Additionally, per 907.4 kg of automotive Li-ion polymer batteries, the cooling requirement for the process is at least 198 MJ (per ton it is 219 MJ) (calculated from the heat capacity of the batteries, 1011.8 J/kg°C, multiplied by 1000 kg and 211 °C). The shredding power requirement is given in the figure and is equivalent to 565.2 MJ [14].</p>	<p>The diagram shows the recycling process for lithium-ion batteries. It starts with 'Shredding and Hammermill' which feeds into 'Separation by Shaker Table'. This leads to 'Aluminum', 'Copper', 'Anode and Cathode Material', and 'Cobalt'. These materials then go through 'Filtering' and 'Filtration' steps, eventually leading to 'Li2CO3' and 'LiCoO2'.</p>

7	Gaines, L., Sullivan, J., Burnham, A., & Belharouak, I. (2011, January). Life-cycle analysis for lithium-ion battery production and recycling. In Transportation Research Board 90th Annual Meeting, Washington, DC (pp. 23-27).	The Company 1 process has been in commercial operation since 1993, processing Li-ion batteries of varying chemistry and other battery types. The company was given a grant in 2009 by the U.S. Department of Energy to recycle Li-ion batteries at its plant. Company 1 has demonstrated how automotive packs would be recycled by actually processing the pack from a Tesla Roadster. First, the battery pack was discharged for safety reasons, and the propylene glycol in the cooling tubes was recovered. The control circuits were removed and tested for possible reuse. The wires and some other metals were removed for recycling. The packs were disassembled and a series of mechanical processes, shown in Figure 3, were used to reduce the size of the cell materials. The three resulting products were fluff, copper cobalt (yielding salable metals such as cobalt, aluminum, nickel, and copper), and cobalt filter cake (reused in appliance coatings). Soda ash was added to the resulting process solution to precipitate out the lithium carbonate. The recycling process is mainly mechanical and chemical, so emissions are kept to a minimum. Since no high-temperature processing is required, energy use is also low. About 60% of the pack materials can be recycled, and a further 10% reused. The fluff, which comprises about 25% of the pack, will be landfilled initially, but the plastic will be recovered when the volumes are high enough to justify the effort.
8	Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H., & Rutz, M. (2012). Development of a recycling process for Li-ion batteries. Journal of power sources, 207, 173-182.	Originally the hydrometallurgical Company 1 process was developed for the safe recycling of spent lithium primary batteries. Today's facility processes lithium secondary battery scrap as well. The scrap is stored in earth covered concrete storage bunkers. Residual electrical energy is removed from larger and more reactive batteries. If necessary the batteries are treated by Company 1's patented cryogenic process, i.e. they are cooled to about -200°C. Lithium, although normally explosively reactive at room temperature, behaves almost inert at this temperature. The batteries are then safely shredded and the materials are separated. Metals from the batteries are collected and sold. The lithium components are separated and converted to lithium carbonate for resale. If the batteries contain cobalt it is also recovered for production of LiCoO2 as new battery electrode material [8,11,12,18-20].	
9	Sullivan, J. L., & Gaines, L. (2012). Status of life cycle inventories for batteries. Energy Conversion and Management, 56, 134-148.	Not all battery recycling operations are pyrometallurgical. Company 1, Inc., employs a series of steps that include the use of hammer mills, screens, and shaker tables to separate three streams of materials, two of which are sold for their high concentrations of Co, Cu, and Al. They also recover the Li as Li2CO3 at 97% purity and sell it to several industries. Unfortunately, no quantitative energy data are yet available on these processes. Although pyrometallurgy has been avoided in this case, the Co, Cu, and Al, in whatever chemical form they remain, must be reprocessed into battery-ready materials. The processes required to do this are not clear, but they certainly would require energy. Finally, one company, Company 1, [12] has developed a process that recovers anode and cathode materials in a form that could potentially be reused in batteries. This effort is novel and unique, as it offers a way to reuse these valuable materials without taking them back to an elemental state. This approach offers the promise of reduced CTG production energy for these batteries. Some preliminary energy values associated with this approach are available at this time, though it is difficult to associate specific energy values with the components. Another advantage of both the Company and Company 1 approaches is the avoidance of air and water emissions associated with winning these materials from earth. The authors are unaware of any infrastructure and approach for recycling NaB batteries. Clearly, the steel, copper, and aluminum in the system can be recycled, but processes for recycling sodium and sulfur from these batteries are apparently still not developed. As indicated above, there is a critical need for life-cycle characterizations (process descriptions and flows) of battery material recycling. Indeed, without them, the potential benefit of recycling these materials may be understated. With the exception of PBA batteries, Table A1 shows available LCI information on battery material recycling is spotty and lacks detail. First, lithium-ion batteries are crushed under a liquid brine solution to prevent emissions and to reduce reactivity of processed batteries. If necessary, the batteries are treated cryogenically to remove residual energy (Georgi-Maschler et al., 2012). Mechanical processes separates the batteries into metal solids, metal-enriched liquid and plastic fluff. The metal solids are sold and the metal-enriched liquid is solidified using filtering technology and then sent off-site to be further purified hydrometallurgically.	
10	W. Novis Smith, S. Swoffer (2014). Process for recovering and regenerating lithium cathode material from lithium-ion batteries, Google Patents	https://www.google.com/patents/US8882007?dq=inassignee%22Company%22&hl=en&sa=X&ved=0ahUKEwWnp2has3MAHVGB4KHmBFRkQ6AEWTAJFbackward-citations	
11	W. Novis Smith, S. Swoffer (2013). Recovery of lithium ion batteries, Google Patents	https://www.google.com/patents/US8616475?dq=inassignee%22Company%22&hl=en&sa=X&ved=0ahUKEwWnp2has3MAHVGB4KHmBFRkQ6AEWTAJFbackward-citations	
12	Amarakoon, S., Smith, J., & Segal, B. (2013). Application of life-cycle assessment to nanoscale technology: Lithium-ion batteries for electric vehicles (No. EPA 744-R-12-001).	Li-ion fluff: mixture of plastics and some steel. Hydrometallurgical Recovery Process: The hydrometallurgical recycling process can be applied to a variety of lithium battery chemistries. Under this process, the batteries are first collected, inspected, and sorted by chemistry. Next, the batteries are fed via a conveyor belt to a hammer mill to remove the paper and plastic. Once prepared, the batteries are processed in a tank, using a feed of alkali process solution (lithium brine) to further shred the cells. The materials are then separated to recover the scrap metal and remove any other non-metallic materials (Company 1, 2010). Four streams result from this process, including: Copper cobalt product: mixture of copper, aluminum, and cobalt cobalt filter cake; mixture of cobalt and carbon Li-ion fluff; mixture of plastics and some steel. Lithium brine: dissolved electrolyte and lithium salts (Company 1, 2009). The copper cobalt product and cobalt filter cake, which comprise about 60% of the battery feed, are sold for further processing to metal refiners. The Li-ion fluff (about 30% of battery feed) is either disposed or sold to steel refiners. The fluff may contain as much as 65% steel, depending on the battery feed. Finally, the brine undergoes further processing, where it is recovered as lithium carbonate (Company 1, 2009; Company 1 2010).	
13	Vadenbo, C. O. (2009). Prospective environmental assessment of lithium recovery in battery recycling. ETH IED-NSSI. ETH Zurich, Zurich, 174.	In the initial step of the process, battery waste is sorted, and cells and batteries deemed to be of suitable chemistries are transferred via a conveyor belt into a crusher. This mechanical treatment step is carried out by a hammer mill while the batteries are submerged in a process solution consisting of lithium brine. The brine is re-circulated from a downstream process step, see Figure 4-7. A so-called Li-ion Fluff can be separated from the rest of the material after the initial crushing. This fraction mainly consists of plastics and some steel, and may either be subjected to direct disposal or steel recovery, depending on the level of steel content. The hammer mill crushing is followed by separation using a shaker table which allows for the so-called Copper Cobalt Product to be extracted. This mixture of metals predominantly consists of copper, cobalt and aluminum and is subsequently sent to other metallurgical operations for separation and recovery. The slurry remaining after this separation step is subsequently transferred to a mixing tank, where it is heated and allowed to react before it is transferred to a holding tank. Dispersed compounds consisting mainly of cobalt and carbon is separated from the dissolved lithium by running the mixture through a filter press, yielding a cobalt filter cake and lithium brine. The filter cake is sent for further metallurgical treatments together with the Copper Cobalt Product, or sold directly as an input to appliance coating. (K. Bruck, personal communication, 28 May 2009) At this stage, the extracted lithium brine can either be re-circulated back to previous steps e.g. serve as an input for the crushing of the battery waste, or be introduced into recirculation tank of the primary lithium battery process line. In the latter case, the brine is transferred to a mixing tank where sodium carbonate (Na2CO3) is added which leads to the formation of insoluble lithium carbonate (Li2CO3) which consequently precipitates out of the solution. The precipitate is subsequently separated by the use of a product filter, and washed, dried and packaged before finally being sent out to customers.
14	Ellis, T. W., & Mirza, A. H. (2011). Battery Recycling: defining the market and identifying the technology required to keep high value materials in the economy and out of the waste dump. 2011 http://www.nist.gov/ipw/pwspw/upload/245_battery_recycling_defining_the_market.pdf .	Cryomilling: Company 1 recycles Li based cells in their facility. In this process the batteries are broken at -196C (-325F, 74K) with the addition of NaOH which converts all Li metal to LiOH. The addition of carbonate species, i.e. CO2-2 converts LiOH to LiCO3 which is easily handled. Cryomilling reduces the chemical activity of the Li materials as chemical reactivity is proportion to the Exp(1/T) where T = Temperature in K. The highly basic nature of NaOH will form an alkali metal salt with the organic carbonates to form glycols. After milling, the electrochemically active materials, i.e. LiCO2 and LiCO3 are separated from plastics and separators by washing on jiggering tables. Li compounds and reclaimed plastics are sold to the market. The mixed LiCO3/LiCO2 material is washed from the packaging scrap, dried and sold as a cake back to the industry. The packaging material is then processed to recover recyclable plastics or sent to a landfill for disposal. The first system is to break the cells under an inert environment such as CO2 or N2 thereby preventing air from initiating a reaction. This however does not reduce uncontrolled reactions with materials within the recycle stream. Cryomilling, i.e. cooling the batteries prior to breaking to a very low temperature, is used by Company 1 for the recycling of Li-ion cells. They first cool the cells to -325F (-175C) which is liquid N2 temperatures prior to breaking as this reduces the rate of any chemical reactions. Additionally the N2 serves as an inert environment. In the Company 1 process, alkali is added in a controlled manner to react with the Li metal.	

15	Sullivan, J. L., Gaines, L., & Burnham, A. (2011, April). Role of recycling in the life cycle of batteries. In TMS 2011 140th annual meeting and exhibition, materials processing and energy materials.	Physical recycling processes: This approach to battery recycling is by its nature a low-energy process. Very little if any heat is employed; the energy that is required is used for running shredders and pumps and for producing liquid nitrogen. An example of this approach, the Company 1 recycling system, is shown in Figure 3 [Coy, 2009]. Company 1's approach involves separating batteries by chemistry, shredding (reducing size) them in a flooded hammer mill, and separating product streams through a combination of a shaker table and two filters. Depending on the feed, liquid nitrogen is used only in two special circumstances: (1) to suppress potential ignition of electrolyte in discarded batteries with high residual energy and (2) to achieve better materials separation when certain battery potting materials were used. The Company 1 system produces three product streams: (1) mixed materials comprised of steel, paper, and plastics; (2) intermediate materials made up of collector foils, mixed metallics, and a little electrode material; and finally (3) a slurry of cathode and anode materials, some of which is carbon. Streams 2 and 3 are of the most value. Substantial amounts of copper, cobalt, nickel, and aluminum are contained in stream 2. Stream 3 produces two fractions: one that contains primarily a cathode material and anode carbon mix, which is rich in cobalt (35% by weight), and the second is a filtrate, from which lithium carbonate (Li ₂ CO ₃) is recovered. This is currently used for other products, but could be purified for use in batteries.	
16	Wend, M., Wietzel, M., Marscheider-Weidmann, F., & Angerer, I. G. (2009). Abschätzung des künftigen Angebots-Nachfrage-Verhältnisses von Lithium vor dem Hintergrund des steigenden Verbrauchs in der Elektromobilität (Doctoral dissertation, Karlsruhe Inst. für Technologie, Fraunhofer-Inst. für System- und Innovationsforschung).	Die Firma X recycelt eine Vielzahl unterschiedlicher Lithium-Batterien. Darunter sind auch große Akkus aus militärischen Verwendungen (bis zu 250 kg). Die Batterien werden, nachdem die Verpackung entfernt wurde, mit flüssigem Stickstoff (< -196°C) gekühlt. Dies erfolgt um die explosiven Reaktionen der Li-haltigen Bestandteile beim Zerkleinern möglichst gering zu halten. Um die Arbeitssicherheit zusätzlich zu erhöhen, laufen ca. 90 % der hier beschriebenen Arbeitsschritte laut X Firmenangaben fengesteuert ab. Im Anschluss erfolgt die Zerkleinerung durch unterschiedliche Scher- und Mahnvorgänge, welche die Batterien je nach Größe vollständig oder nur teilweise durchlaufen. Diese Zerkleinerung findet in einem NaOH-Säurebad (Natriumhydroxid) statt, das die Neutralisierung säurehaltiger Bestandteile und die Auflösung von Lithium und Lithium-Salzen bewirkt. Die so gewonnenen Lithium-Bestandteile werden ausgefällt und danach zu Li-Karbonat weiterverarbeitet. Der nach der Lithium-Ausfällung übriggebliebene Schlamm wird zur Kobalt-Gewinnung weiteren Löse- bzw. Ausfällschritten ausgesetzt. Wasserstoff und organische Materialien verbrennen an der Oberfläche des Säurebads und die so anfallenden Verbrennungsabgase werden gefiltert an die Atmosphäre geleitet. Papier- und Plastikrückstände werden zur Verwertung oder Beseitigung von der Oberfläche gefiltert. Die im Säurebad übergabebenen großen Teile werden in einer Hammerröhre erneut gemahlen und dann in metallische und nichtmetallische Komponenten getrennt. Eine schematische Darstellung dieses Prozesses ist Abbildung 4-2 dargestellt.	<pre> graph TD A[Li-Batterien] --> B[Kühlung (-196°C)] C[Verpackungsmaterial] --> B B --> D[große Kutter] D --> E[Scherische Scherung] E --> F[Rotationschere] F --> G[Hammerröhre] G --> H[Nahm-Lösung] H --> I[Metallische, Papier, Kunststoff] H --> J[G-Salze] H --> K[Kobalt Gewinnung] </pre>
17	AUFTRAG, I., & UMWELTBUNDESAMTES, D. (2001). Untersuchung von Batterieverwertungsverfahren und -anlagen hinsichtlich ökologischer und ökonomischer Relevanz unter besonderer Berücksichtigung des Cadmiumproblems.	Einen neuartigen Prozess zur Verwertung lithiumhaltiger Batterien. Das Unternehmen kann alle lithiumhaltigen Batterien recyceln, unabhängig von ihrer Grösse und dem zugrunde liegenden chemischen System. Das Einsatzspektrum reicht dabei von klassischen Gerätebatteriefornaten bis zu Spezialbatterien aus dem militärischen Bereich. Die angelieferten Lithiumbatterien werden nach System und Grösse sortiert bis zu ihrer Verarbeitung in Betonbunkern gelagert. Die Verarbeitung beginnt nach der Entfernung von Verpackungsmaterial mit einer Abkühlung der Batterien durch Eintauchen in ein Bad mit flüssigen Stickstoff. Die Abkühlung erfordert je nach Grösse der Batterien 1 bis 24 Stunden [96]. Durch die so erreichbaren sehr niedrigen Temperatur (der Siedepunkt von Stickstoff liegt bei minus 196 °C) wird die hohe Reaktionsfähigkeit des in den Batterien enthaltenen metallischen Lithiums und anderer Bestandteile soweit herabgesetzt, dass die weiteren Behandlungsschritte vergleichsweise gefahrlos durchgeführt werden können. Dennoch werden nach Firmenangaben die meisten Arbeitsschritte zur Sicherheit der Arbeiter fengesteuert ausgeführt [285]. Die gekühlten Batterien werden abgesichert bzw. geschreddert und mit einer alkalischen Lösung (Natrium- hydroxid, NaOH) zur Reaktion gebracht. Die Batterien werden je nach Grösse durch bis zu zwei weitere Zerkleinerungs- und Reaktionsstufen geleitet, damit die vollständige Abreaktion der reaktiven Bestandteile gewährleistet ist. Dabei helfender Wasserstoff wird kontrolliert an der Oberfläche des Bades durch Kontakt mit aufschwimmenden, brennendem Lithium verbrannt. Lithium und Lithiumsalze werden in der Lauge gelöst und gezielt ausgefällt. Die Laugezusatzstoffe (Metallschlacke, Kunststoffe) werden nach Auflösung des Lithiums den Tanks entnommen und können weiteren Verwertungsprozessen zugeführt oder beseitigt werden [36]. Das ausgefallene Lithium wird als Lithiumcarbonat vermarktet.	
18	Diaz, J. C. (2015). Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America.	X operates a comprehensive lithium battery processing facility. Customers include the US military, and oil service companies around the globe. Directional drilling equipment used by oil companies employs lithium batteries, which X processes and recycles. The facility has been in business for several years. It accepts all batteries, then sorts them and sends the chemistries that they do not process at the site to other partners. Batteries are sorted and fed via conveyor into a hammermill crusher in a lithium brine- process solution, consisting of dissolved electrolytes and lithium salts. The process stream is then separated from the lithium-ion "fluff," which is a mixture of plastics and some steel. If the steel content is sufficient it is sent for steel recovery; otherwise, it is disposed of. The steel content may sometimes be as high as 65 percent, depending on the feedstock. The process stream then passes through a shaker table to produce a copper-cobalt product: a mixture of copper (Cu), aluminum (Al) and cobalt (Co). This product is sold to primary-metal producers. The slurry is then added to a mix tank and for holding tank. The slurry is passed through a filter press to produce a cobalt filter cake: a mixture of cobalt and carbon (C). This product is sold to primary-metal producers. The remaining slurry is sent to the primary process line to recover lithium in the form of lithium carbonate. Four streams are produced: 1. Li-ion "fluff"—mix of plastics and some steel 2. Copper-cobalt product (Cu, Al, and Co) 3. Cobalt filter cake (Co and C) 4. Lithium brine slurry—dissolved electrolytes and lithium salts.	

Company 2:

Company 2	References	Content	Figures
1	SALOOJEE, F., & LLOYD, J. LITHIUM BATTERY RECYCLING PROCESS.	The process is able to treat 320 tpa of lithium batteries, including primary and secondary battery types. The process uses a combination of physical and chemical treatment steps to produce lithium carbonate. The battery scrap is first treated by crushing, magnetic separation and density separation to produce a fine powder. The powder is then fed to a hydrometallurgical process, consisting of hydrolysis, leaching and precipitation steps. Lithium is recovered as Li ₂ CO ₃ and cobalt is recovered as cobalt hydroxide. Crushing of the batteries is a two-step process, taking place in a rotary shredder. The crusher operates in an atmosphere of CO ₂ and 10-35% argon (Tedar & Foudraz, 2010). The CO ₂ reacts with any elemental lithium to form Li ₂ CO ₃ , which is less reactive than elemental lithium. The crushed batteries are fed to a physical separation process. Some of the off-gas from the crushing step is used to create an inert atmosphere above the hydrolysis reaction. The remaining off-gas is fed to the lithium precipitation step. The components of the crushed battery scrap are separated by screening, magnetic separation and densimetric separation. For the screening step, vibrating screens of 3 mm and 500 µm are used (Tedar & Foudraz, 2010). The <3 mm fraction contains metal oxides and carbon. This is further screened on the 500 µm screen. The <500 µm fraction is rich in cobalt. Lithium is contained in this fraction. The >500 µm fraction is rich in copper. The cobalt-rich fraction is sent to the hydrometallurgical treatment process and the copper-rich fraction is combined with the steel and sold. The <3 mm fraction is treated by magnetic separation. The magnetic fraction contains the steel from the battery casings. The non-magnetic fraction is further separated on a densimetric table. The low-density, non-magnetic fraction contains paper and plastics. Non-ferrous metals report to the high-density, non-magnetic fraction. Each of these fractions is sold. The fine material from the physical separation process is treated by hydrolysis. The material is suspended in stirred water. A solution of lithium hydroxide is added to achieve a pH of 12-13 (Tedar & Foudraz, 2010). Lithium from the electrodes dissolves to produce lithium salts in solution. The hydrolysis reaction generates hydrogen. Inert gas from the crushing step is used to vent off the hydrogen. The metal oxides and carbon are suspended in solution and are separated out by filtration. The lithium-containing solution is sent to a lithium precipitation step. Lithium is precipitated from the alkaline leach solution as Li ₂ CO ₃ using CO ₂ gas. The source of CO ₂ is the off-gas from the crushing stage. Precipitation occurs at a pH of 9, which is achieved by the addition of acid. The precipitate is washed with a CO ₂ -saturated solution and dried at 105°C (Tedar & Foudraz, 2010). The stream containing suspended solids from the hydrolysis step is leached in sulfuric acid at a pH of 3 and a temperature of 80°C (Tedar & Foudraz, 2010). The metal oxides dissolve, leaving carbon in the residue. The leach product is filtered and the solution is purified prior to cobalt precipitation. In the purification process, copper and iron are removed from solution. Copper is cemented out by the addition of steel shots. Soda is added to increase the pH to 3.85 in order to precipitate iron. The copper- and iron-free solution is fed to cobalt precipitation. Cobalt is recovered from solution either by electrolysis, or by precipitation as Co(OH) ₃ through the addition of sodium hypochlorite. The remaining solution contains some lithium and is sent to the lithium precipitation step. The steps involved in the Recupyl process are shown in Figure 4-1 (Tedar & Foudraz, 2010).	
2	Vadenbo, C. O. (2009). Prospective environmental assessment of lithium recovery in battery recycling. <i>ETH IED-NSSI, ETH Zurich</i> , Zurich, 174.	Mechanical preparation of the battery waste is performed under an inert atmosphere, consisting of a mixture of carbon dioxide and argon, where the latter of the two gases typically makes up 10-35%. The use of carbon dioxide during the preparation will reduce the reactivity of any elemental lithium present by the formation of Li ₂ CO ₃ . By monitoring the concentration of oxygen and internal pressure, and consequently injecting more of the inert gas mixture only when certain threshold-values are exceeded, the consumption of inert gas can be reduced. The preparation consists of crushing and shearing of cells and batteries and generates a finely-sized charge which is transferred to the physical treatment process. (Tedar et al. 2007) In the physical treatment step, three separation processes takes place, generating four different fractions. Firstly, the charge from the mechanical preparation is passed over a vibrating screen with a mesh size smaller than or equal to 3 mm. The undersized fraction separated in this step contains metal oxides and carbon and will go on either in the recycling process or an additional screening at 500 µm. The remaining oversized material is subsequently subjected to separation according to magnetic properties and density, yielding a magnetic fraction (mainly steel from casings), a dense non-magnetic fraction (non-ferrous metals), and a low-density non-magnetic fraction (paper and plastics). (Tedar et al. 2007) The fine charged obtained from the screenings is thereafter suspended in heavily stirred water for the subsequent leaching and hydrolysis step. Aqueous lithium hydroxide is added to the solution to bring the pH up to above 12. Hydrogen gas is generated as the charge is hydrolyzed and to reduce the risk for explosion posed by this reaction the inert gas from the mechanical pre-treatment is utilized to vent off any hydrogen released from the bath. This hydrolysis step produces an alkaline solution of lithium salts and a suspension of metal oxides and carbon. (Tedar et al. 2007) The lithium contained in the aqueous solution is precipitated by reducing the pH of the solution to 9 and using the CO ₂ -containing inert gas from the mechanical treatment as a source of precipitation agent. The obtained precipitated Li ₂ CO ₃ is subsequently washed with carbon dioxide-saturated water followed by drying at 105°C. The remaining aqueous solution is still rich in dissolved lithium, due to the solubility of Li ₂ CO ₃ and thus requires additional treatment (the type of treatment is not specified in the Patent). (Tedar et al. 2007) The metal oxides obtained in the suspension from the fine leaching are dissolved in warm sulfuric acid (ERM 2006). The pH in the mixture is less than 3. This leaching step results in a solution and a carbon-containing pulp. Copper impurities are cemented out of the solution by the use of steel shots. Iron present in the solution is precipitated by raising the pH to 3.85 through the addition of soda. The solution resulting from the purification is then oxidized by the addition of sodium hypochlorite (NaClO) to precipitate cobalt (III) hydroxide. Alternatively, the separation of cobalt can be carried out through electrolysis. The lithium remaining in the solution is sent to step where lithium is precipitated out of solution as described above. (Tedar et al. 2007)	
3	US7820317 B2: https://www.google.com/patents/US7820317	The invention relates to a method for treating all types of lithium anode cells and batteries by means of a hydrometallurgical process at room temperature. The treatment method enables cells and batteries comprising a metallic lithium-based anode or an anode containing lithium incorporated in an anodic insertion compound to be treated under safe conditions, thus enabling the metallic casings, electrode contacts, cathode metal oxides and lithium salts to be separated and recovered.	
4	Hanisch, C., Diekmann, J., Steiger, A., Haselrieder, W., & Kwade, A. (2015). Recycling of Lithium-Ion Batteries. <i>Handbook of Clean Energy Systems</i> .	Company 2's underlying mechanical and hydrometallurgical process, shown in Figure 13, for the recycling of LIBs was developed during the X project within the Y between 2000 and 2003 (Vadenbo, 2009). According to Vadenbo, the process shown in the patent application XY (Tedar and Foudraz, 2007), which is designed for various lithium-based batteries, will be outlined concerning the recycling route for LIBs. In a first step, the LIBs are crushed in an enclosure with defined and controlled atmosphere and pressure. The generated atmosphere consists of argon, carbon dioxide, or a mixture of these two gases (10-35 vol% argon) replacing the measured content of oxygen to preferred concentrations close to 5000 ppm. The comminution process is separated into two steps: the first one is realized in a slow shearing machine (preferably less than 11 rpm), whereas the second step is realized in a rotor system with a moderate speed (preferably less than 90 rpm). The comminuted material is then sent to a combined separation process consisting of a vibrating screen, a magnetic separator, and a densimetric table that leads to four different fractions. The undersized fraction falling through the sieve mesh is rich in metal oxides and carbon; the magnetic fraction consists of stainless steel from the cell casing; the dense, nonmagnetic fraction consists of nonferrous materials, whereas the low density, nonmagnetic fraction includes separator materials and plastics. Following this, only the first mentioned undersized fraction is further processed by screening to reduce the content of copper to under 0.3%. Subsequently, the obtained fine fraction with high cobalt content can be processed in hydrometallurgical process steps by initial suspending in heavily stirred water. Here, the high turbulence leads to the release of metal and lithium oxides. By adding lithium hydroxide, the pH value increases and gaseous H ₂ is generated by hydrolysis. At the end of the reaction and after a filtration step, a solution containing lithium salts and a suspension of metal oxides and carbon are obtained (Tedar and Foudraz, 2007). By adding CO ₂ , the lithium salt Li ₂ CO ₃ is precipitated. Alternatively, a neutralization with phosphoric acid (H ₃ PO ₄) leads to the formation of Li ₃ PO ₄ . The mixture containing metal oxides and carbon can be processed by an additional acid leaching/ filtration step with the result that cobalt can be obtained by means of electrolysis (Vezzini, 2014).	
5	Defra, 2006. Battery Waste Management Life Cycle Assessment.	A variant of the Recupyl process, called Valibat, is used to recycle Li-ion batteries. This process includes treating the batteries with inert gas once they are shredded. The products obtained include lithium salts and a number of metals. The process is shown diagrammatically in Figure 14.	
6	EP2450991 A1, http://www.google.com/patents/EP2450991A1?tsdoc	The invention relates to a process for treating all the end-of-life accumulator and battery types except the alkaline, zinc-carbon ones and lead accumulators. The process comprises a first phase of physical operations and a second phase of chemical operations which all together allow the recovery of copper and plastic materials typically contained in nickel-metal hydride accumulators, lithium ion batteries and accumulators, primary lithium batteries. The process is characterized by the use of a purification operation by means of a solvent which allows obtaining lithium products (Li ₂ CO ₃), cobalt (Co/CeSO ₄ /CoCO ₃) and nickel (Ni/NiCO ₃) with a high purity grade.	

Company 3:

Company 3	References	Content	Figures
1	Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegh, H. & Rutz, M. (2012). Development of a recycling process for Li-ion batteries. Journal of power sources, 207, 173-182.	The company X mainly runs a mechanical processing plant for Li-ion battery cells. The batteries are crushed in CO ₂ gas atmosphere. Thereby the volatile organic electrolyte evaporates and is collected as non-usable condensate. A subsequent material separation is done and the different material fractions are sold and represent feedstock materials in other processes [10-17].	
2	Briffaerts, K., Sprinckx, C., Van der Linden, A., & Vrancken, K. (2009). Waste battery treatment options: comparing their environmental performance. Waste management, 29(8), 2321-2331.	The X process has been developed for the safe treatment of zinc carbon and alkaline batteries, regardless of their mercury content. The installation is located in Y. X waste batteries are treated. Also foreign waste batteries with a relatively high mercury content are treated here. In the past, waste batteries used to have a high mercury content. Currently, the addition of mercury to zinc carbon and alkaline batteries is banned by European legislation X applies a pyrometallurgical process which is optimised for the recovery of mercury through a complex cleaning system for fume gases and waste water. The waste batteries are treated in a shaft furnace (600-700 °C). The mercury evaporates and is eventually recycled as metallic mercury. Next, the remains of the batteries are treated in an electrically heated induction melting furnace (1500 °C). Ferromanganese and slag are produced. A constant ferromanganese quality (about 40% Mn) is guaranteed. Compared with an electric arc furnace, the energy consumption per tonne treated waste batteries is relatively high. In accordance with Y legislation, the produced slag is disposed of on a landfill for inert waste. Most of the zinc is converted into zinc bars and nuggets (standard quality) in a zinc condenser. Part is collected as zinc oxide. Hydrometall produces zinc sulphate and filter cake from the zinc oxide. Other applications are possible. The filter cake is converted in Wastz oxide and slag. The fume gases from the induction melting furnace contain considerable amounts of CO and are used as a fuel in the process.	
3	Vadenbo, C. O. (2009). Prospective environmental assessment of lithium recovery in battery recycling. ETH IED- NSSI. ETH Zürich, Zürich, 174.	In the patent application (Zenger et al. 2003) it is claimed that the recycling method developed by X is capable of processing portable lithium-based cells and batteries from all existing industrial classes. The process description does not, however, disclose any information on compound level concerning which materials are recovered in the process. The process flow chart is presented in figure 4-3. The following process description for the recycling of lithium-ion cells and batteries, developed by X, is based on U.S. Patent Application 2003/0180604 A1 (Zenger et al. 2003). As the treatment commences, the cells and batteries are already placed in a protective environment made up of gaseous carbon dioxide. The Patent Application includes descriptions of methods for transportation and storage of these cells and batteries under protective environment, and it is assumed that batteries destined for the recycling process comes under such conditions. The cells and batteries are fed into the first step of the treatment where they are batchwise mechanically disassembled by, for example, a shredder. During this treatment, the protective atmosphere is maintained by continuously adding carbon dioxide. (Zenger et al. 2003) When the dismantling is completed, moist air is added to the protective atmosphere to facilitate neutralization of the processed material. Upon the completion of this neutralization step, the protective environment is released and subsequently treated in a gas scrubber to reduce air-born emissions from the process. (Battrec 2009; Zenger et al. 2003). The scrap material is subsequently leached and washed in an acidified aqueous solution. This process step results in a solid fraction and leaching liquor which contains soluble chemical compounds. The metal-containing solid fraction can now be separated from the liquid and treated to remove impurities, e.g. plastics, through the use of pyrolysis, and subsequently subjected to further mechanical treatment to separate various metal compounds. The leaching liquor is also subjected to further treatment for the recovery of various chemical substances (the identity of these substances are unspecified (unavailable literature). The last step of the process involves the appropriate disposal of any residual waste (the types of waste are unspecified in the available literature) (Zenger et al. 2003).
4	Zenger, T., Krebs, A., Van Deutschem, H., J. H., Battrec Industrie AG (2003) Method of and apparatus for dismantling and storage of objects comprising alkali metal containing substances, U.S. Pat. App. 2003/0180604 A1	There is disclosed a method of and an arrangement for dismantling and storage of objects comprising alkali metal containing substances, in particular lithium containing batteries, in the presence of a protective atmosphere, wherein the protective atmosphere is carbon dioxide. The arrangement comprises a gas-tight chamber for bringing the objects under a protective environment, and a gas-tight chamber for dismantling the objects within the protective atmosphere of carbon dioxide gas.
5	CEC. 2015. Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America. Montreal, Canada: Commission for Environmental Cooperation. 103 pp.	In Y, X operates a mechanical processing plant for Li-ion battery cells. The batteries are crushed in a CO ₂ gas atmosphere, whereby the volatile organic electrolyte evaporates and is collected as non-usable condensate. The crushing operation is performed at room temperature in order to prevent any oxidation reaction from occurring. The next step is "neutralization" of metallic lithium by adding a controlled amount of an oxygen-containing reactant, such as air. After neutralization of lithium, the batteries are further crushed and undergo material separation. The different material fractions are sold as feedstock materials in other processes.73	
6	Defra, 2006. Battery Waste Management Life Cycle Assessment.	X use an alternative process to treat Li-ion batteries, where the main safety concern is to render the highly flammable batteries inert. The process is shown diagrammatically in Figure 1.6. The Li-ion batteries are fed to a crushing unit, where they are crushed in a controlled atmosphere. The released lithium is neutralised and other products (chrome-nickel steel, cobalt, non-ferrous metals, manganese oxide and plastic) are separated in a multistage separating plant.

Company 4:

Company 4	References	Content	Figures
1	Gaines, L., Sullivan, J., Burnham, A., & Beharouk, I. (2011, January). Life-cycle analysis for lithium-ion battery production and recycling. In Transportation Research Board 90th Annual Meeting, Washington, DC (pp. 23-27).	Figure 2 is a simplified flow chart of the XY process (M. Caffarey, X July 2010, unpublished data). X is a European company that processes all types of batteries in two locations. It collects spent batteries and ship them to its plant in X. The material collected is fed into the smelter with no pre-processing. Organic components in the batteries (plastics, electrolyte solvents, and carbon electrodes) are burned. X counts this as recovery because the heat fuels the smelter and the carbon serves as a reducing agent for some of the metal. The main products are cobalt and nickel, which are then sent to a refinery in Y, Y where the CoO2 is made; it is subsequently forwarded to Y to produce LiCoO2 for batteries (using new purchased lithium). Recovery of cobalt and nickel not only saves about 70% of the energy needed for their primary production from sulfide ores, but also avoids the significant SO2 emissions from such production. Other metals, such as iron, can be recovered as well. The lithium and aluminum from the smelter currently go to the slag, which find low-value uses, but the company is investigating ways to recover lithium for higher-value uses such as batteries. Waste gases are subjected to high temperature to avoid emissions of dangerous organics like furans or dioxin. The company claims a 93% recovery rate for Li-ion batteries (metals 69%, carbon 10%, plastics 15%), but a much smaller percentage actually comes out as usable high-value material.
2	Sullivan, J. L., & Gaines, L. (2010). A review of battery life-cycle analysis: state of knowledge and critical needs (No. ANL/ESD10-7). Argonne National Laboratory (ANL).	X an advanced materials company, has major operations devoted to battery recycling. Their primary interest is to recover Ni and Co, the latter of which currently commands high returns in the secondary marketplace. Although at this time X does not recover the Li derived from Li-ion batteries, they could do so in the future if lithium prices in the secondary market become attractive. In fact, the battery recycling industry has concerns about the reduction of cobalt use in Li-ion batteries, since reduced yields of Co in that recycling stream could make their processes uneconomical. For Li-ion batteries, X breaks up the batteries, feeds them into a smelting furnace, where metals are recovered, and subsequently sends them to a refiner to get the desired purity of Cu, Fe, Zn, Ni(OH)2, and CoO2. The CoO2 is sent to another operation to produce LiCoO2 for use in new batteries. X claims that using recycled Co reduces the production energy for LiCoO2 by 70%. This is a tremendous improvement.	
3	Dunn, J. B., Gaines, L., Barnes, M., Wang, M., & Sullivan, J. (2012). Material and energy flows in the materials production, assembly, and end-of-life stages of the automotive lithium-ion battery life cycle (No. ANL/ESD12-3). Argonne National Laboratory (ANL).	X has developed a smelting process (Figure 14) in which batteries, which may be dismantled to the module level, are fed to a high-temperature shaft furnace along with a slag-forming agent that typically includes limestone, sand, and slag. The shaft furnace has three heating zones. In the first, called the pre-heating zone, temperatures are below 300C. This lower temperature reduces explosion risks. In this stage, the electrolyte slowly evaporates. The next zone is called the plastics pyrolyzing zone and operates at about 700C. The burning of the battery's plastics helps maintain the high operating temperature and reduces the overall energy consumption of the smelting step. The last zone is the smelting and reducing zone, where the metallic material transforms to a slag containing lithium, aluminum, silicone, calcium, and some iron. If manganese is present in the cathode material, it will also go into the slag. In addition, an alloy with copper, cobalt, nickel, and some iron forms. This step may be heated by a plasma torch and can reach temperatures between 1,200 and 1,450C. Gases leaving the smelter are treated in a post-combustion chamber heated to above 1,150C with a plasma torch. It is critical in this stage to capture halogens from the electrolyte through injection of calcium- or sodium- containing products. Alternatively, ZnO can be used to achieve this capture and avoid formation of dioxins or furans. Additional gas clean-up steps are also necessary. The fate of metals is the key to this process. Lithium is entrained in the slag; it is not economical or energy efficient to recover it. Slag can be used as a beneficial aggregate in concrete. The alloy undergoes two leaching steps that recover copper and iron, likely as salts. To recover cobalt, HCl is added to the process in a solvent extraction step, yielding cobalt chloride (CoCl2). This compound is oxidized to cobalt oxide (Co3O4) then fired with Li2CO3 to yield LiCoO2 which may need further treatment before it can be used in new batteries. Nickel can also be recovered as nickel hydroxide (Ni(OH)2) from additional processing steps after solvent extraction.
4	Kosaraju, S. (2012). A review of the importance of recycling lithium-ion batteries for lithium, in view of impending electric vehicle industry. Chalmers University of Technology	X (Chent, Broussely et al. 2007) is one of major producers of materials for lithium-ion cathodes (LiCo or other mixed-metal materials). The aim of the X closed-loop process, shown in Figure 22, is to provide to treat end-of-life lithium-ion batteries and production scraps. Batteries are directly introduced into a furnace without any pre-processing, e.g. crushing or dismantling. The increase in temperature and reducing conditions are closely managed so that no explosion can occur and the totality of Co and steel is recovered in the metallic phase. This metallic phase is then atomized into a very fine powder and further refined in the Co refinery. The other product formed during the first smelting step is a pure inert slag. By managing the smelting conditions, no metal can be found in the slag. The slag can be re-used in construction, concrete or even as raw material in replacement of pure limestone and silica in the special steel industry.
5	Sonoc, A., Jeswiet, J., & Soo, V. K. (2019). Opportunities to Improve Recycling of Automotive Lithium Ion Batteries. Procedia CIRP, 29, 752-757.	The X process is a smelting process for spent lithium ion and nickel metal hydride batteries (see Fig. 1). An alloy of valuable materials (Co, Cu, Ni, Fe) is obtained from the smelter and it is then treated hydrometallurgically (acid leaching followed by chemical precipitation to metal salts) to give recovered metals. All of the lithium, aluminium and manganese from the LIBs ends up in the slag and are not recovered. For 1 ton of batteries 5000 MJ of heat are needed for the smelter and gas clean-up.

6	Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H., & Rutz, M. (2012). Development of a recycling process for Li-ion batteries. <i>Journal of power sources</i> , 207, 173-182.	<p>The X process represents a dedicated combined pyro- and hydrometallurgical battery recycling process for spent Li-ion and NiMH batteries. The battery scrap is directly melted down in a purpose-built shaft furnace without any kind of pre-treatment. X is also a producer of cathode material for Li-ion batteries, i.e. the recycling process aims at a closed-loop recovery of cobalt and nickel in form of LiCoO_2 and Ni(OH)_2. Ignoble metals, such as aluminum and lithium, are lost whereas copper, iron and manganese are recovered in an aqueous solution. Organic materials as well as carbon are burned and used as reducing agents [27–31]. Currently the only comparable industrial recycling process is X process. Both the here presented as well as the X process are specially dedicated to Li-ion batteries but the latter is already established with a yearly capacity of 4000 t battery scrap. The main difference is the missing pre-treatment in the X process. That means only noble metals, such as chromium, cobalt, copper and nickel, are recovered. Another disadvantage of the X process is the fact that the electrolyte as well as the lithium content is not recovered. X announces a recycling efficiency of approximately 70 mass-% but the calculation method is not in compliance with the EU Battery Directive since the thermal as well as the material utilisation are taken into account. According to X this adds up to 20 mass-% for plastics and up to 15 mass-% for the graphite. X considers these battery components as recycled. From the economical side of view the process seems to be more cost-effective because of the missing pre-treatment steps. But it has to be mentioned that the metal alloy has to be further processed hydrometallurgically for a separate cobalt and nickel recovery. In contrast the cobalt alloy produced in the electric arc furnace can directly be used as master alloy for cobalt-based superalloys. A big disadvantage of all pyrometallurgical recycling processes is the fact that lithium cannot be recovered. Thus a combination of pyro- and hydrometallurgical process steps is necessary as is the case for the X process.</p>	
7	Cheret, D. & Santen, S., 2007. Battery recycling, Umicore, US patent 7 169 206 B2	<p>Process for the recovery of Co or Ni, comprising the steps of: Preparing a metallurgical charge comprising Fe, slag formers, and a useful load containing either one or both of Co and Ni; - feeding the charge to a shaft furnace; and - smelting the charge so as to form a Co or Ni-bearing alloy, an Fe-bearing slag and a gaseous phase, characterised in that the useful load comprises at least 30 wt. % electrochemical batteries or their scrap, and in that the redox potential in the furnace is chosen so as to slag at least 20 wt. % of the Fe, and at most 20 wt. % of the Co or 20 wt. % of the Ni present in the charge.</p> <p>1200 kg of Li-ion batteries with stainless steel cans are introduced in a shaft furnace together with 200 kg of slag from the steel industry containing typically 40 wt. % CaO, 34 wt. % SiO_2 and 11 wt. % Al_2O_3, 110 kg of SiO_2, 100 kg of limestone and 400 kg of cokes during 455 minutes, corresponding to a feed rate of 319 kg/h. Preheated air at 500° C, is injected via 3 burners at the bottom of the shaft furnace with a flow of 130 m³/h. The metal bath temperature is 1450° C, and the temperature of the gases at the top of the furnace is 445° C. In the post-combustion chamber, the temperature is maintained at 1100–1150° C. 538 kg of slag and 679 kg of Fe-bearing alloy are formed. Their composition and a material balance of the experiment are given in Table 1.</p>	
8	Vadenbo, C. O. (2009). Prospective environmental assessment of lithium recovery in battery recycling. ETH IEO- NSSI, ETH Zürich, Zürich, 174.	<p>The process developed by X is a single-furnace pyrometallurgical treatment method for lithium-ion and lithium-polymer cells and batteries, as well as nickel metal hydride (NiMH) batteries. The process is carried out in a shaft furnace, where batteries and slag formers, coke and limestone are fed into the furnace, and slag and molten metal is extracted. The process does not require precautionary measures in order to prevent explosions from the presence of elemental lithium due to the absence of mechanical pre-treatment steps (Cheret 2007). The following process description for the recycling of lithium-ion cells and batteries, developed by X is based on Cheret (2007) and U.S. Patent 7,169,206 (Cheret et al. 2007). See Figure 4-8 for the process flow chart. The main focus of the process is the recovery of cobalt and/or nickel. Cobalt is commonly found in lithium-ion and lithium-polymer batteries, whereas nickel is introduced into the process through the treatment of NiMH batteries. The batteries are mixed together with slag formers, coke (400 kg, not accounted for in Table 4-3), limestone and sand (for amounts and composition see Table 4-3) and introduced into the top of a shaft furnace. Here, the temperature in the furnace is at its lowest, which prevents explosions resulting from electrolytes evaporating too fast while being trapped inside the batteries. Other input to the process is air, which can be oxygen-enriched, preheated to 500°C and which is introduced at the bottom of the furnace (Cheret et al. 2007). Based on the events and the reactions occurring as a result of the gradual temperature increase in the process, the furnace can be divided into three zones. In the upper zone, the batteries are preheated by hot gases rising through the furnace. The temperature of the charge in the preheating zone typically remains under 300°C which allows the electrolyte to be slowly evaporated. As the charge is transferred to the downwards in the furnace, it reaches the so-called plastic pyrolysis zone. In this second process zone, temperatures of about 700°C occur, allowing plastics to be eliminated from the battery packs. The energy released from this step contributes to heating the gases that subsequently rise towards the preheating zone. (Cheret et al. 2007) In the last zone smelting and reduction of the remaining material takes place. The charge is transformed into two fractions: a slag and an alloy (see Table 4-4 for amount and composition). The slag is mainly formed by compounds containing aluminum (Al), silicon (Si), calcium (Ca) and to some extent iron (Fe), in the process, lithium also ends up in the slag in the form of lithium oxide. The slag can be used in for example the construction or concrete industry (Cheret 2007). The alloy fraction is predominantly made up of residual iron, copper, cobalt, and possibly nickel. The temperature of the recovered fractions is between 1200 and 1450°C upon extraction from the furnace. (Cheret et al. 2007) The alloy is subsequently leached with sulfuric acid in a hydrometallurgical step with extracts metals like cobalt, copper, nickel and iron. The recovery rates of the various compounds are shown in Table 4-5. The cobalt recovery consists of multiple process steps, including dissolution and solvent extraction, which finally produces pure cobalt chloride (CoCl_2) (X, 2006). The cobalt chloride is thereafter oxidized in a furnace and mixed with lithium and transformed into lithium cobalt oxide (LiCoO_2) which serves as an input for lithium-based battery production (X, 2006). The waste gases that reach the top of the shaft furnace at a temperature of about 445°C are subsequently treated with a plasma torch to prevent condensation of the gaseous compounds and to eliminate toxic emissions like halogens or volatile organic compounds (VOC). The plasma torch heats the exhaust gas to above 1150°C before it enters the post-combustion chamber. Injection of various Ca- or Na-based products or ZnO via the torch allows for the capture of free halogens which otherwise could contribute to the formation of toxic dioxins or furans (X 2006; McKay 2002). In the post-combustion chamber the gas is rapidly cooled down by adding water vapor to prevent the formation of more complex compounds. The final step of the gas treatment is a conventional dust filtering installation.</p>	
9	Kettner, B., Karl, U., Möst, D., & Ullrich, S. (2009). Lithium-Ionen-Batterien: Stand der Technik und Anwendungspotenzial in Hybrid-, Plug-In Hybrid- und Elektrofahrzeugen. Wissenschaftliche Berichte FZKA, 7503.	<p>Ein Recyclingkonzept über ein Schmelz- und Raffinationsverfahren, genannt X, wurde von der Firma X (einem der Hauptproduzenten von Kathodenmaterialien) in den Jahren 2002/2003 erarbeitet und bietet eine geschlossene Lösung zur Entsorgung von kleinen Lithium-Ionen-Batterien bis hin zu großen Batteriesystemen. Die Batterien werden hier- bei, wie in Abbildung 4-7 dargestellt, komplett in einem Ofen eingeschmolzen, wobei Be- standteile wie Nickel, Kobalt und Stahl in eine Metallphase übergehen. Aus dieser Schmelze werden in einem Raffinationsschritt die reine Metalle rückgewonnen und wieder zur Herstel- lung von Kathodenmaterialien eingesetzt. Die übrigen Materialien, unter anderem auch Li- thium, bilden eine inerte Schlacke, die z.B. im Baugewerbe verwendet werden kann. Die Elektrolyte und Kunststoffe tragen als Brennstoff zur Prozessenergiegewinnung bei. Über ein Gasreinigungssystem werden schädlichen Gase gefiltert (UM/08). Die im X Prozess erzielten Recycling-Raten für kleine Lithium-Ionen Akkumulatoren mit LiCoO_2-Kathode und Graphit-Anode sind in der nachfolgenden Tabelle 6 dargestellt. Während 80% des Kobalts recycelt werden können, bleibt bei diesem Verfahren das Lithium vollständig in der Schlacke gebunden und wird somit nicht rückgewonnen. Neben dem Schmelzprozess können auch hydrometallurgische Verfahren zur Rückgewin- rung der Metalle eingesetzt werden. Das Unternehmen Z hat dazu einen Prozess ent- wickelt, bei dem zunächst die Reaktivität der Zellen durch Abkühlen in flüssigem Stickstoff herabgesetzt und die Batterie dann im gefrorenen Zustand geschreddert wird. Nach Abtren- nung von Plastikteilen können über nasschemische Verfahren bestimmte Verbindungen, z.B. Li_2CO_3 als Ausgangsmaterial zur Herstellung neuer Kathodenmaterialien gewonnen werden.</p>	

Company 5:

Company 5	References	Content	Figures
1	Chapras, A., & Świątowska, J. (Eds.). (2015). Lithium process chemistry. Resources, extraction, batteries, and recycling. Elsevier.	The technology is based on a multistep process that begins with mechanical pretreatment to remove covers and printed circuit boards. During pretreatment the Li-ion battery packs are disassembled and the single battery cells are laid open. Thereby a material fraction that contains electronic parts and plastics is generated. The second process step comprises pyrolysis in a resistance-heated retort furnace at a maximum temperature of 250 °C. The battery cells are deactivated safely for further processing. The volatile organic electrolyte evaporates and is caught in a downstream condenser. In the third-process step the deactivated cells are crushed safely in a second mill and in a disintegrator. After crushing, classification and sorting are performed by means of a vibrating screen, magnetic separation in a drum separator and air separation in a zigzag classifier. The generated material fractions are an iron-nickel and an aluminum fraction (both from battery casings), an electrode foil fraction, and a fine fraction, which contains the electrode material. For better handling and charging into the electric arc furnace the fine fraction is agglomerated to pellets using molasses as a binding agent. The pellets have a cobalt content of approximately 30 mass % and a lithium content of approximately 3 mass %. Due to the high graphite content of approximately 30 mass %, and problems during pyrometallurgical processing, a thermal pretreatment is performed. The pellets are charged into a rotary kiln to halve the graphite content to approximately 15% at a temperature of 800 °C. Cobalt is recovered as an alloy. The slag and the fine dust are further processed in a hydrometallurgical route to recover lithium. Because of its high vapor pressure and its high oxygen affinity, lithium leaves the furnace via the off-gas as oxide during processing. The material is leached with sulfuric acid and lithium is precipitated with sodium carbonate. A lithium carbonate with a purity higher than 99 mass % can be generated. A process flow sheet is shown in Figure 7.5.	
2	Li-ion battery recycling X VOK process. Available at: http://www.accurac.de/treatment-and-recycling/technologies/li-batteries [cit. 12.01.15].	This newly developed, innovative Lion process technology enables a high proportion of recovered metals from portable Li-ion and Li-P batteries (RE>55%) at minimized cost	
3	Georgi-Maschler T., Friedrich B., Weyhe R., Haegri H., Rutz M. Development of a recycling process for Li-ion batteries. J Power Sources 2012;207:1736-62.	During pre-treatment the Li-ion battery packs are disassembled and the single battery cells are laid open. Thereby a material fraction which contains the electrode foil fraction an aqua regia dissolution is done to determine the copper and aluminum contents. All ICP-OES analysis results are listed in Table 3. The most valuable material fraction is the fine fraction which contains almost all of the cobalt and lithium in form of metal oxides as well as the graphite (see Fig. 4). Measurements with a laser diffraction sensor (Sympatec Helos KFS Oesia) show a density of 2.68 g cm ⁻³ and 80% of the particles have a size smaller than 100 µm. For better handling and charging into the electric arc furnace the fine fraction is agglomerated to pellets using molasses as binding agent. The pellets have a cobalt content of approx. 30 mass-% and a lithium content of approx. 3 mass-%. Due to the high graphite content of approx. 30 mass-% and therefore problems during pyrometallurgical processing a thermal pre-treatment is done. The pellets are charged into a rotary kiln to halve the graphite content to approx. 15 mass-% at a temperature of 800 °C. Cobalt is recovered as an alloy. The slag and the fine dust are further processed in a hydrometallurgical route to recover lithium. Because of its high vapor pressure and its high oxygen affinity, lithium leaves the furnace via the off-gas as oxide during processing. The material is leached with sulfuric acid and lithium is precipitated with sodium carbonate. A lithium carbonate with a purity higher than 99 mass % can be generated. A process flow sheet is shown in Figure 7.5.	
4	Reuter, M., Hudon, C., Van Schaik, A., Heiskanen, K., Meskers, C., & Hagelüken, C. (2013). Metal recycling: Opportunities, limits, infrastructure. A Report of the Working Group on the Global Metal Flows to the International Resource Panel, UNEP.	The X recycling concept is illustrated in Figure 103: Li-ion batteries are disassembled into casings, waste of electronic and electrical equipment (WEEE), plastics and battery cells. Casings, plastics and WEEE are processed in existing recycling infrastructure. The battery cells are deactivated at 500°C to evaporate organics, to ensure safe handling and to remove halogenides such as fluorides and chlorides safely. Afterwards, the battery cells are shredded and separated into a Cu/Al-foil and a fine fraction. The foil fraction is integrated into the existing recycling infrastructure. The fine fraction contains the valuable electrode materials Co, Ni, Mn, and Li of a Li-ion cell (electrode material, EM). The EM is pyrometallurgically processed to gain the valuable metals in an alloy and to concentrate the lithium in the generated fine dust. Afterwards, the fine dust is treated hydrometallurgically for generating a high quality Li-compound such as Li2CO3. The pyrometallurgical treatment of the battery cells is done in a submerged (electric) arc furnace (SAF). SAFs are ideal for battery re-cycling because of their high flexibility concerning input materials and process parameters, their high productivity for relatively small plant sizes, and their low off-gas emissions. The process can be adapted to different input materials simply by choosing an adequate slag composition. Basically, the slag phase controls the process. Depending on the slag's composition, a metal accumulates in the alloy, in the slag phase or in the fine dust. To operate such a process, the slag characteristics basically, solubility of metals, density, melting point and viscosity at process temperature have to be controlled.	

Appendix C – Comparison Matrix

Company	Process	Material	Amount (in metric tons)	Material Price (US\$ metric tons)	Global Warming Potential (GWP 100 in kg CO2-eq)	Source (market price - 4Q:2018H1)	Benefit (US\$ metric tons)	Environmental Effect (Pressure-Equivalent)	Base- Price/ JE (t3)	Recycling Efficiency (RR)	Legislation RE = 90 % (YES/NO)	Source	Lithium Recycling (YES/NO)
Company 1	Mechanical Treatment/ Hydrothermal Treatment	Copper	0.0800	4,692.10		InvestmentMine	375.37						
		Aluminum	0.0500	1,591.90		InvestmentMine	103.47						
		Nickel	0.0400	8,960.00		InvestmentMine	184.84						
		Lithium carbonate	0.0300	6,000.00		Quintel	180.00						
		Cobalt	0.1750	23,800.00	518.84	InvestmentMine	415.00	2,50E-10	1.98E+13	below 70%	YES	Directive 2006/46/EU on Batteries and Accumulators and Waste Batteries and Accumulators	YES
		Steel Iron	0.3350	300.00		Quintel	61.50						
		Electricity (in kWh)	0.3350	0.10		Plastic News	0.00						
		Water	776.0000	0.13		Statista.com - Europe	25.00						
		Soda ash	0.0300	1.31		Water Cost Index - Global	0.20						
		CO2e	0.0184	25.48		ICS	0.75						
				55.48		The World Bank	497.93	2.9E-10	1.98E+13				YES
Company 2	Mechanical Treatment/ Hydrothermal Treatment	Copper	0.0800	4,692.10		InvestmentMine	375.37						
		Aluminum	0.0500	1,591.90		InvestmentMine	103.47						
		Nickel	0.0400	8,960.00		InvestmentMine	184.84						
		Lithium carbonate	0.0300	6,000.00		Quintel	180.00						
		Steel Iron	0.3350	300.00	124.93	Quintel	61.50	6,30E-10	8.66E+12	below 70%	YES	Directive 2006/46/EU on Batteries and Accumulators and Waste Batteries and Accumulators	YES
		Polymer	0.1400	0.00184		Plastic News	0.00						
		Electricity (in kWh)	1.1225	0.10		Statista.com - Europe	0.00						
		Water	0.7200	1.31		Water Cost Index - Global	0.04						
		Limestone	0.1160	101.00		Infrastructure Materials Corp.	11.72						
		Lithium hydroxide	0.0250	8000.00		Office	200.00						
		Sulfuric acid	0.0250	139.50		Yellity - Producer Price Index	23.44						
		CO2e	1.1225	55.48		The World Bank	71.51	6.3E-10	8.66E+12				YES
Company 3	Mechanical Treatment/ Pyrothermal Treatment	Copper	0.0800	4,692.10		InvestmentMine	375.37						
		Aluminum	0.0500	1,591.90		InvestmentMine	103.47						
		Nickel	0.0400	8,960.00		InvestmentMine	184.84						
		Lithium carbonate	0.0300	6,000.00		Quintel	60.00						
		Cobalt powder	0.2000	19,570.00	1122.23	Shanghai Metal Market	394.00	5,20E-10	8.66E+12	below 70%	YES	Directive 2006/46/EU on Batteries and Accumulators and Waste Batteries and Accumulators	YES
		Steel Iron	0.2500	300.00		Quintel	61.50						
		Electricity (in kWh)	0.3350	0.10		Statista.com - Europe	25.00						
		Water	1.0000	1.31		Water Cost Index - Global	1.1						
		Sodium hydroxide	0.3500	125.00		Yellity - Producer Price Index	43.79						
		CO2e	1.1225	55.48		The World Bank	62.26	5.2E-10	8.66E+12				YES
Company 4	Pyrothermal Treatment	Copper	0.0800	4,692.10		InvestmentMine	304.80						
		Nickel	0.0251	8,960.00		InvestmentMine	225.00						
		Cobalt	0.1313	23,800.00		InvestmentMine	312.46						
		Steel Iron	0.2288	300.00		Quintel	60.00						
		Electricity (in kWh)	1.667000	0.10		Statista.com - Europe	50.11						
		Water	6.1100	1.31	224.25	Water Cost Index - Global	8.00	1,00E-10	3.05E+13	above 50%	YES	Directive 2006/46/EU on Batteries and Accumulators and Waste Batteries and Accumulators	NO
		Slagformers	0.1660	27.50		Improvent	4.57						
		Sand Binder	0.1500	40.00		Plastic News	0.00						
		Limestone	0.0810	101.00		Infrastructure Materials Corp.	8.90						
		Coke	0.3330	294.86		U.S. Department of Commerce	98.17						
		Sulfuric acid	0.1680	139.50		Yellity - Producer Price Index	23.44						
		CO2e	0.2243	55.48		The World Bank	12.44	1,0E-10	3.05E+13				NO
Company 5	Mechanical Treatment/ Pyrothermal Treatment/ Hydrothermal Treatment	Copper	0.0800	4,692.10		InvestmentMine	375.37						
		Aluminum	0.0500	1,591.90		InvestmentMine	92.29						
		Nickel	0.0415	8,960.00		InvestmentMine	371.84						
		Lithium carbonate	0.0300	6,000.00		Quintel	415.00						
		Cobalt	0.1750	23,800.00		InvestmentMine	415.00						
		Steel Iron	0.1838	300.00		Quintel	55.14						
		Electricity condensate	0.0280	50,020.00	871.24	PR Newswire	840.56	1,40E-10	1.56E+13	above 50%	YES	Directive 2006/46/EU on Batteries and Accumulators and Waste Batteries and Accumulators	YES
		Polymer	0.1400	0.00184		Plastic News	0.00						
		Electricity (in kWh)	930.0000	0.10		Statista.com - Europe	36.00						
		Water	0.1500	1.31		Water Cost Index - Global	0.20						
		Sand Binder	0.0710	40.00		Improvent	2.84						
		Slagformers	0.1287	27.50		Plastic News	0.00						
		Sulfuric acid	0.0710	139.50		Yellity - Producer Price Index	3.54						
		CO2e	0.8713	55.48		The World Bank	48.34	4,30E-10	1.56E+13				YES

Appendix D – Umberto NXT LCA Data

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