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
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

IN

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UNIVERSITY OF RHODE ISLAND
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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.
ACKNOWLEDGMENTS

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<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
</tr>
<tr>
<td>ELCA</td>
<td>Environmental Life Cycle Assessment</td>
</tr>
<tr>
<td>ELCD</td>
<td>European Reference Life Cycle Database</td>
</tr>
<tr>
<td>EOL</td>
<td>End-Of-Life</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HTP</td>
<td>Human Toxicity Potential</td>
</tr>
<tr>
<td>I-P-O</td>
<td>Input- Process- Output</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
</tr>
<tr>
<td>LIBs</td>
<td>Lithium-Ion Battery (-ies)</td>
</tr>
<tr>
<td>NEEDS</td>
<td>New Energy Externalities Developments for Sustainability</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory Data Base</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-In Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>TETP</td>
<td>Terrestrial Ecotoxicity Potential</td>
</tr>
<tr>
<td>US</td>
<td>United States of America</td>
</tr>
<tr>
<td>WEEE</td>
<td>Waste Electrical and Electronic Equipment</td>
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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.
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 biotreatment 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.
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 (LiMO₂) used in automotive applications, such as the most common material lithium cobalt oxide (LiCoO₂), lithium manganese oxide (LiMn₂O₄), lithium nickel oxide (LiNiO₂), lithium vanadium oxide (LiV₂O₅), and LiFePO₄ (Kang et al., 2006). The Chevy Volt for example uses a Mn-spinel and mixed metal cathode, the Coda Sedan uses LiFePO₄, the Nissan Leaf uses LiMn₂O₄ and the Tesla Model S uses LiCoO₂ (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](image)

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 (Maehlß, 2012).

The various material compositions of LIBs, especially regarding the different types of cathode materials, such as LiMO₂, LiCoO₂, or LiFePO₄ (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)

<table>
<thead>
<tr>
<th>Material</th>
<th>Current Price (US$/ m ton)</th>
<th>Source (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>8,960.0</td>
<td>(InvestmentMine, 2016)</td>
</tr>
<tr>
<td>Cobalt</td>
<td>23,800.0</td>
<td>(InvestmentMine, 2016)</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1,591.9</td>
<td>(InvestmentMine, 2016)</td>
</tr>
<tr>
<td>Copper</td>
<td>4,692.1</td>
<td>(InvestmentMine, 2016)</td>
</tr>
<tr>
<td>Steel</td>
<td>300.0</td>
<td>(Quandl, 2016)</td>
</tr>
<tr>
<td>Lithium Carbonate</td>
<td>6,000.0</td>
<td>(Lithium Investing News, 2016)</td>
</tr>
</tbody>
</table>
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.

![Industrialized Recycling Processes for EV LIBs](image)

**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](image)

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](image)

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](image)

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**

<table>
<thead>
<tr>
<th>Companies Recycling Processes (RP) for Lithium-ion EV Batteries</th>
<th>Recycling Efficiency Lithium-ion EV Batteries (W) x 3 WF (Weighting)</th>
<th>CO₂ Recycling Saving Potential Lithium-ion EV Batteries (W) x 2 WF (Weighting)</th>
<th>Recycling Capacity Lithium-ion EV Batteries (W) x 1 WF (Weighting)</th>
<th>Process Rating PR = ( \sum (K \times W) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP - X1 Company 1</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>RP - X2 Company 2</td>
<td>?</td>
<td>?</td>
<td>2.300 t</td>
<td>3</td>
</tr>
<tr>
<td>RP - X3 Company 3</td>
<td>?</td>
<td>?</td>
<td>5.000 t</td>
<td>5</td>
</tr>
<tr>
<td>RP - X4 Company 4</td>
<td>&gt; 50% (correct)</td>
<td>?</td>
<td>4.000 t</td>
<td>5</td>
</tr>
<tr>
<td>RP - X5 Company 5</td>
<td>&gt; 50% (correct)</td>
<td>?</td>
<td>7.000 t</td>
<td>7</td>
</tr>
</tbody>
</table>

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.
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.

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


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
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., CO$_2$eq, 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

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Theme</th>
<th>Indicator</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>Natural Resources</td>
<td>Material Use</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Energy Use</td>
<td>kWh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water Consumption</td>
<td>m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waste Creation</td>
<td>kg</td>
</tr>
<tr>
<td>Pollution</td>
<td>Global Warming Potential</td>
<td></td>
<td>kg CO₂</td>
</tr>
<tr>
<td></td>
<td>Acidification Potential</td>
<td></td>
<td>kg SO₂</td>
</tr>
<tr>
<td></td>
<td>Human Toxicity, Eco-Toxicity</td>
<td></td>
<td>kg 1,4-DCB</td>
</tr>
</tbody>
</table>

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 (eco-toxicity). Toxic emissions are inorganic air pollutants, such as NH₃, SO₂ and NOₓ, 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-DCBeq equivalent (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.
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 (Ormazaet 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).
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 (kg CO$_2$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)

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition (mass in%)</th>
<th>Composition (kg/ metric ton spent LIBs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCoO₂</td>
<td>27.5</td>
<td>275</td>
</tr>
<tr>
<td>Lithium</td>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>Cobalt</td>
<td>17.5</td>
<td>175</td>
</tr>
<tr>
<td>Oxygen</td>
<td>8.0</td>
<td>80</td>
</tr>
<tr>
<td>Steel/ Ni</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>24.5</td>
<td>245</td>
</tr>
<tr>
<td>Nickel</td>
<td>20.5</td>
<td>205</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>40</td>
</tr>
<tr>
<td>Cu/ Al</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>14.5</td>
<td>145</td>
</tr>
<tr>
<td>Aluminum</td>
<td>8.0</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>65</td>
</tr>
<tr>
<td>Carbon</td>
<td>16.0</td>
<td>160</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>3.5</td>
<td>35</td>
</tr>
<tr>
<td>Polymer</td>
<td>14.0</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>100.0%</td>
<td>1000 kg</td>
</tr>
</tbody>
</table>

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 where 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

<table>
<thead>
<tr>
<th>Flow</th>
<th>Quantity</th>
<th>Unit</th>
<th>Source</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw material inputs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spot LIBS</td>
<td>1000</td>
<td>kg</td>
<td>Functional Unit</td>
<td></td>
</tr>
<tr>
<td>Sodium Ash</td>
<td>30</td>
<td>kg</td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td>Process data from Gaines et al., 2011</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity, medium voltage</td>
<td>776</td>
<td>kWh</td>
<td>Ecoinvent</td>
<td>Electricity on a medium voltage level; global average (GLIO)</td>
</tr>
<tr>
<td>Water consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process water, main supply</td>
<td>150/l</td>
<td></td>
<td>Ecoinvent</td>
<td>Process water consumption; global average (GLIO)</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed Plastics, Steel, to recycler</td>
<td>338</td>
<td>kg</td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Copper/ Cobalt/ Aluminum, to industry</td>
<td>255</td>
<td>kg</td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Mixed Mono/Oxides and Carbon, to industry</td>
<td>255</td>
<td>kg</td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Lithium Carbonate, to industry</td>
<td>30</td>
<td>kg</td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Solid waste</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residue, to landfill</td>
<td>102</td>
<td>kg</td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td>Disposal of inert waste to inert landfill, Switzerland, 1995</td>
</tr>
<tr>
<td>Water, to sewer</td>
<td>150/l</td>
<td></td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td>Market for wastewater, average, Switzerland, 2000</td>
</tr>
<tr>
<td><strong>Unit Operations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryogenic cooling</td>
<td>Ecoinvent</td>
<td></td>
<td>This activity ends with the production of liquefied nitrogen by cryogenic air separation. It was assumed that this process is equivalent to the cryogenic cooling process step of Company 1.</td>
<td></td>
</tr>
<tr>
<td>Shredder</td>
<td>Ecoinvent</td>
<td></td>
<td>This activity in-shredding components from manual dismantling. It was assumed that this process is equivalent to the shredding process step of Company 1.</td>
<td></td>
</tr>
<tr>
<td>Hammermill</td>
<td>Dunn, J. et al., 2012</td>
<td></td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>Staker nite</td>
<td>Sonse et al., 2015; Diaz et al., 2015; Dunn et al., 2012; Gaines et al., 2011</td>
<td></td>
<td>Source 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.</td>
<td></td>
</tr>
<tr>
<td>Scrubber</td>
<td>Ecoinvent</td>
<td></td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>Hydrometallurgical treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixing Tank</td>
<td>Ecoinvent</td>
<td></td>
<td>This activity is mixing the emissions resulting from the shredding process. It was assumed that this process is equivalent for Company 1.</td>
<td></td>
</tr>
<tr>
<td>Filter Press</td>
<td>Ecoinvent</td>
<td></td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>Flash evaporator</td>
<td>Ecoinvent</td>
<td>Tank et al., 2008</td>
<td>This activity is evaporates the circulating lithium brine in order to generate lithium carbonate in the end. It was assumed that these processes are equivalent for Company 1.</td>
<td></td>
</tr>
</tbody>
</table>
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 occurring 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 compents (Dunn et al., 2012), all copper and aluminum components are recycled from the FU. In relation to the

59
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 (Li₂CO₃). 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 where 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

Input/Output Graph - LCA of EV LIB Recycling Process of Company 1 (transport between the processes is highlighted with an asterisk (*); recirculated transport between the processes is highlighted with two asterisks (**)
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.
Figure 22. Umberto NXT LCA Model Company 1
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-DCB eq and the ecotoxicity potential is 0.22 kg 1,4-DCB eq.

![Figure 23. Company 1: Environmental Impact of Impact Categories](image)

**Figure 23. Company 1: Environmental Impact of Impact Categories**

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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Mechanical Treatment</th>
<th>Hydrometallurgical Treatment</th>
<th>Total</th>
<th>Total (PE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP 100 (kg CO₂-eq)</td>
<td>210.80 kg / 40.6%</td>
<td>308.04 kg / 59.4%</td>
<td>518.84 kg / 100%</td>
<td>2.17E-10</td>
</tr>
<tr>
<td>HTP (kg 1,4-DCB-eq)</td>
<td>31.10 kg / 45.1%</td>
<td>37.88 kg / 54.9%</td>
<td>68.98 kg / 100%</td>
<td>2.88E-11</td>
</tr>
<tr>
<td>TETP (kg 1,4-DCB-eq)</td>
<td>0.07 kg / 31.8%</td>
<td>0.15 kg / 68.2%</td>
<td>0.22 kg / 100%</td>
<td>9.20E-14</td>
</tr>
</tbody>
</table>
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 CO$_2$eq; 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 CO$_2$eq; 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**

<table>
<thead>
<tr>
<th>Process Step</th>
<th>GWP100 (kg CO$_2$eq)</th>
<th>HTP (kg 1,4-DCBeq)</th>
<th>TETP (kg 1,4-DCBeq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>89.5</td>
<td>6.1</td>
<td>0.004</td>
</tr>
<tr>
<td>Cryogenic Cooling</td>
<td>108.8</td>
<td>3.1</td>
<td>0.002</td>
</tr>
<tr>
<td>Shredding Emissions</td>
<td>76.8</td>
<td>26.2</td>
<td>0.07</td>
</tr>
<tr>
<td>Landfilling Residues</td>
<td>243.5</td>
<td>33.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Disposal Wastewater</td>
<td>0.1</td>
<td>0.1</td>
<td>0.00</td>
</tr>
<tr>
<td>Rest</td>
<td>0.1</td>
<td>0.1</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>518.8</strong></td>
<td><strong>68.9</strong></td>
<td><strong>0.22</strong></td>
</tr>
</tbody>
</table>

The person-equivalent (PE) creates create 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 preforming 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.
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 2.5E-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

<table>
<thead>
<tr>
<th>Flow</th>
<th>Quantity</th>
<th>Unit</th>
<th>Source</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw material inputs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent LIBs</td>
<td>1000 kg</td>
<td>Functional Unit</td>
<td>Ecoinvent, Defra, 2006</td>
<td>process is a mechanical and hydrometallurgical process for the recycling of spent LIBs to produce lithium carbonate.</td>
</tr>
<tr>
<td>Reagent</td>
<td>25 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Generic inorganic chemicals; global average (GLO), 2000</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>182 kWh</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Electricity on a medium voltage level; global average (GLO)</td>
</tr>
<tr>
<td>Water consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process water, main supply</td>
<td>720 l</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Process water consumption; global average (GLO)</td>
</tr>
<tr>
<td>Sulfuric Acid</td>
<td>126 l</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Primary process value (Defra, 2006); Sulfuric Acid, 2000</td>
</tr>
<tr>
<td>Lime</td>
<td>115 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Primary process value (Defra, 2006); Lime, 2000</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt salt, to cobalt producer</td>
<td>340 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Lithium salt, to lithium producer</td>
<td>198 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Iron and steel, to steel industry</td>
<td>245 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Non-ferrous metals, to reprocessor</td>
<td>65 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Copper, to reprocessor</td>
<td>80 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Paper and plastic, to refining</td>
<td>140 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Solid wastes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum, to landfill</td>
<td>339 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Disposal of gypsum to in inert landfill, Switzerland, 1995</td>
</tr>
<tr>
<td>Residue, to landfill</td>
<td>282 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Disposal of inert waste to in inert landfill, Switzerland, 1995</td>
</tr>
<tr>
<td>Water, to sewer</td>
<td>337 kg</td>
<td></td>
<td>Ecoinvent, Defra, 2006</td>
<td>Market for wastewater, average, Switzerland, 2000</td>
</tr>
</tbody>
</table>

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 inter 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.
Figure 26. Umberto NXT LCA Model Company 2
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 CO$_2$eq. 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.

![Company 2: Environmental Impact of Impact Categories](image)

**Figure 27. Company 2: Environmental Impact of Impact Categories**

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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Mechanical Treatment</th>
<th>Hydrometallurgical Treatment</th>
<th>Total</th>
<th>Total (PE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP 100 (kg CO$_2$-eq)</td>
<td>4.83 kg / 0.4%</td>
<td>1320.10 kg / 99.6%</td>
<td>1324.93 kg / 100%</td>
<td>5.54E-10</td>
</tr>
<tr>
<td>HTP (kg 1,4-DCB-eq)</td>
<td>0.33 kg / 0.2%</td>
<td>179.09 kg / 99.8%</td>
<td>179.42 kg / 100%</td>
<td>7.50E-11</td>
</tr>
<tr>
<td>TETP (kg 1,4-DCB-eq)</td>
<td>0.01 kg / 1.3%</td>
<td>0.79 kg / 98.7%</td>
<td>0.80 kg / 100%</td>
<td>3.34E-13</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Process Step</th>
<th>GWP100 (kg CO₂eq)</th>
<th>HTP (kg 1,4-DCBeq)</th>
<th>TETP (kg 1,4-DCBeq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>20.9</td>
<td>1.4</td>
<td>0.00</td>
</tr>
<tr>
<td>Landfilling Gypsum</td>
<td>817.0</td>
<td>111.4</td>
<td>0.49</td>
</tr>
<tr>
<td>Landfilling Residues</td>
<td>486.7</td>
<td>66.4</td>
<td>0.31</td>
</tr>
<tr>
<td>Disposal Wastewater</td>
<td>0.2</td>
<td>0.1</td>
<td>0.00</td>
</tr>
<tr>
<td>Rest</td>
<td>0.1</td>
<td>0.1</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>1324.9</td>
<td>179.4</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Figure 28 shows the results after preforming 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](image)
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 6.3E-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 fed 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

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Quantity</th>
<th>Unit</th>
<th>Source</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spent LIBs</td>
<td>1000</td>
<td>kg</td>
<td>Functional Unit</td>
<td></td>
</tr>
<tr>
<td>Sodium Hydroxide</td>
<td>350</td>
<td>kg</td>
<td>Eco Invent, Defra, 2006</td>
<td>Generic inorganic chemicals, global average (GLO), 2000</td>
</tr>
<tr>
<td>Electricity</td>
<td>800</td>
<td>kWh</td>
<td>Eco Invent, Defra, 2006</td>
<td>Electricity on a medium voltage level, global average (GLO)</td>
</tr>
<tr>
<td>Water consumption</td>
<td>1,000</td>
<td>l</td>
<td>Eco Invent, Defra, 2006</td>
<td>Process water consumption, global average (GLO)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Quantity</th>
<th>Unit</th>
<th>Source</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel/ Nickel, to steel/ nickel industry</td>
<td>245</td>
<td>kg</td>
<td>Eco Invent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Cu-Powder, to cobalt industry</td>
<td>209</td>
<td>kg</td>
<td>Eco Invent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Non ferrous metals, to metal industry</td>
<td>249</td>
<td>kg</td>
<td>Eco Invent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Lithium powder, to industry</td>
<td>10</td>
<td>kg</td>
<td>Eco Invent, Defra, 2006</td>
<td>Process data adjusted to FU</td>
</tr>
<tr>
<td>Solid wastes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastics, to incinerator</td>
<td>140</td>
<td>kg</td>
<td>Eco Invent, Defra, 2006</td>
<td>Market for incineration (waste), Switzerland, 1995</td>
</tr>
<tr>
<td>Residue, to landfill</td>
<td>273</td>
<td>kg</td>
<td>Eco Invent, Defra, 2006</td>
<td>Disposal of inert waste to in inert landfill, Switzerland, 1995</td>
</tr>
<tr>
<td>Water, to sewer</td>
<td>1000</td>
<td>l</td>
<td>Eco Invent, Defra, 2006</td>
<td>Market for wastewater, average, Switzerland, 2000</td>
</tr>
<tr>
<td>Sulphur Dioxide</td>
<td>40</td>
<td>g</td>
<td>Defra, 2006</td>
<td>Primary process value (Defra, 2006); Sulphur Dioxide, 2000</td>
</tr>
<tr>
<td>Chlorine</td>
<td>40</td>
<td>g</td>
<td>Defra, 2006</td>
<td>Primary process value (Defra, 2006); Chlorine, 2000</td>
</tr>
</tbody>
</table>

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 Deutkom, 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.
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 CO$_2$eq. The impact potential for human toxicity potential is 110.68 kg 1,4-DCBeq and the ecotoxicity potential is 0.31 kg 1,4-DCBeq.

![Figure 31. Company 3: Environmental Impact of Impact Categories](image)

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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Mechanical Treatment</th>
<th>Pyrometallurgical Treatment</th>
<th>Total</th>
<th>Total (PE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP 100 (kg CO$_2$-eq)</td>
<td>18.47 kg / 1.7%</td>
<td>1103.76 kg / 98.3%</td>
<td>1122.23 kg / 100%</td>
<td>4.69E-10</td>
</tr>
<tr>
<td>HTP (kg 1,4-DCB-eq)</td>
<td>1.26 kg / 1.1%</td>
<td>109.42 kg / 98.9%</td>
<td>110.68 kg / 100%</td>
<td>4.63E-11</td>
</tr>
<tr>
<td>TETP (kg 1,4-DCB-eq)</td>
<td>0.001 kg / 0.2%</td>
<td>0.31 kg / 99.8%</td>
<td>0.31 kg / 100%</td>
<td>1.32E-13</td>
</tr>
</tbody>
</table>
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 CO$_2$eq; HTP: 37.74 kg 1,4-DCBeq; TETP: 0.02 kg 1,4-DCBeq) and landfill of residue (GWP 100: 486.7 kg CO$_2$eq; 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 landflling 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

<table>
<thead>
<tr>
<th>Process Step</th>
<th>GWP100 (kg CO₂eq)</th>
<th>HTP (kg 1,4-DCBeq)</th>
<th>TETP (kg 1,4-DCBeq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>91.9</td>
<td>6.2</td>
<td>0.00</td>
</tr>
<tr>
<td>Incineration of Plastics</td>
<td>542.0</td>
<td>37.4</td>
<td>0.00</td>
</tr>
<tr>
<td>Landfilling Residues</td>
<td>486.7</td>
<td>66.4</td>
<td>0.31</td>
</tr>
<tr>
<td>Disposal Wastewater</td>
<td>0.2</td>
<td>0.1</td>
<td>0.00</td>
</tr>
<tr>
<td>Rest</td>
<td>1.3</td>
<td>0.5</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>1122.2</td>
<td>110.7</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Figure 32 shows the results after preforming 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.

![Company 3: Normalization of Impact Categories (Year 2000 [ReCiPe])](image)

**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 5.2E-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

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>Flow</th>
<th>Quantity</th>
<th>Unit</th>
<th>Source</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material inputs</td>
<td>Spent LIBs</td>
<td>1000 kg</td>
<td>Functional Unit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td>100 kg</td>
<td>The authors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td>50 kg</td>
<td>The authors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td>100 kg</td>
<td>The authors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coke</td>
<td>100 kg</td>
<td>The authors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limestone</td>
<td>100 kg</td>
<td>The authors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>Electricity, medium voltage (CEO)</td>
<td>1,607 kWh</td>
<td></td>
<td>Envirotex, Dowell et al. 2008, Dunn et al. 2014</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water, air consumption</td>
<td>610 l</td>
<td></td>
<td>Envirotex, Dowell et al. 2008, Dunn et al. 2014</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Process air of 400°C</td>
<td>1,042 l</td>
<td></td>
<td>Envirotex, Dowell et al. 2008, Dunn et al. 2014</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUTPUTS</th>
<th>Flow</th>
<th>Quantity</th>
<th>Unit</th>
<th>Source</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product output</td>
<td>Slag, to construction or concrete industry</td>
<td>585 kg</td>
<td></td>
<td>The authors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alloy, to industry</td>
<td>448 kg</td>
<td></td>
<td>The authors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>610 l</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nitric Acid, to landfill</td>
<td>108 l</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bank Gases</td>
<td>329 kg</td>
<td></td>
<td>Envirotex, Dowell et al. 2008</td>
<td></td>
</tr>
</tbody>
</table>

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.
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 CO$_2$eq. 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](image)

**Figure 35. Company 4: Environmental Impact of Impact Categories**

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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Pyrometallurgical Treatment</th>
<th>Total</th>
<th>Total (PE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP 100 (kg CO$_2$-eq)</td>
<td>224.25</td>
<td>224.25</td>
<td>9.37E-11</td>
</tr>
<tr>
<td>HTP (kg 1,4-DCB-eq)</td>
<td>17.31</td>
<td>17.31</td>
<td>7.24E-12</td>
</tr>
<tr>
<td>TETP (kg 1,4-DCB-eq)</td>
<td>0.02</td>
<td>0.02</td>
<td>7.94E-15</td>
</tr>
</tbody>
</table>
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 CO\textsubscript{2}eq; 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 CO\textsubscript{2}eq; 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

<table>
<thead>
<tr>
<th>Process Step</th>
<th>GWP100 (kg CO₂eq)</th>
<th>HTP (kg 1,4-DCBeq)</th>
<th>TETP (kg 1,4-DCBeq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>192.3</td>
<td>12.9</td>
<td>0.01</td>
</tr>
<tr>
<td>Landfilling Residues</td>
<td>31.6</td>
<td>4.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Disposal Wastewater</td>
<td>0.3</td>
<td>0.2</td>
<td>0.00</td>
</tr>
<tr>
<td>Rest</td>
<td>0.1</td>
<td>0.1</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>224.3</td>
<td>17.3</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 36 shows the results after preforming 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 1.0E-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
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

<table>
<thead>
<tr>
<th>Flow</th>
<th>Quantity</th>
<th>Unit</th>
<th>Source</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent LIBs</td>
<td>1000 kg</td>
<td>Functional Unit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snel</td>
<td>70 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Limestone</td>
<td>129 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Sulfuric Acid</td>
<td>128 l</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Primary value from company 2, Delta, 2006, comparable</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity, medium voltage (GLO)</td>
<td>930 kWh</td>
<td>Ecoinvent/ Company 1, 2</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Electricity on a medium voltage level; global average (GLO)</td>
</tr>
<tr>
<td>Water/ Air consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process water, main supply</td>
<td>150 kg</td>
<td>Ecoinvent</td>
<td></td>
<td>Process water consumption; global average (GLO)</td>
</tr>
<tr>
<td><strong>OUTPUTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe-N fraction, to industry</td>
<td>184 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Al fraction, to industry</td>
<td>25 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Electrode foil, to industry</td>
<td>114 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Plastic covers/ electronic fractions, to recycling</td>
<td>150 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Electrolyte condenser, to industry</td>
<td>28 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Cobalt alloy, to industry</td>
<td>217 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Lithium salt (as Li2CO3), to lithium producer</td>
<td>198 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water, to sewer</td>
<td>150 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Market for wastewater, average, Switzerland, 2000</td>
</tr>
<tr>
<td>Sulfuric acid, to landfill</td>
<td>128 l</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Primary value from company 2, Delta, 2006, comparable</td>
</tr>
<tr>
<td>Residue, to landfill</td>
<td>197 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
<tr>
<td>Electrolyte condenser, to landfill</td>
<td>7 kg</td>
<td>Ecoinvent</td>
<td>Georgi-Maschler et al., 2012</td>
<td>Laboratory value from company, adjusted to FU (1000 kg)</td>
</tr>
</tbody>
</table>

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 slide 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-Maschler et 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-Maschler et 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.
Figure 37. I-P-O Model of Company 5

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

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.

![Company 5: Environmental Impact of Impact Categories](image)

**Figure 39. Company 5: Environmental Impact of Impact Categories**

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Mechanical Treatment</th>
<th>Pyrometallurgical Treatment</th>
<th>Hydrometallurgical Treatment</th>
<th>Total (kg)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP 100 (kg CO₂eq)</td>
<td>221.05 kg / 25.4%</td>
<td>120.89 kg / 13.9%</td>
<td>529.30 kg / 60.7%</td>
<td>871.24 kg</td>
<td>100%</td>
</tr>
<tr>
<td>HTP (kg 1,4-DCBeq)</td>
<td>70.29 kg / 43.9%</td>
<td>12.99 kg / 8.1%</td>
<td>76.89 kg / 48.0%</td>
<td>160.17 kg</td>
<td>100%</td>
</tr>
<tr>
<td>TETP (kg 1,4-DCBeq)</td>
<td>0.18 kg / 36.0%</td>
<td>0.02 kg / 4.0%</td>
<td>0.30 kg / 60.0%</td>
<td>0.50 kg</td>
<td>100%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Process Step</th>
<th>GWP100 (kg CO₂eq)</th>
<th>HTP (kg 1,4-DCBeq)</th>
<th>TETP (kg 1,4-DCBeq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>107.3</td>
<td>7.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Shredding Emissions</td>
<td>198.1</td>
<td>68.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Furnace Waste</td>
<td>35.6</td>
<td>6.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Landfilling Residues</td>
<td>474.9</td>
<td>64.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Landfilling Sulfuric Acid</td>
<td>55.1</td>
<td>13.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Disposal Wastewater</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Rest</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>871.2</td>
<td>160.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

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.

![Company 5: Normalization of Impact Categories (World, Year 2000 [ReCiPe])](image)

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 4.3E-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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>Mechanical Treatment/ Hydrometallurgical Treatment</td>
<td>Copper</td>
<td>0.0800</td>
<td>4,692.00</td>
<td>InvestmentMine</td>
<td>375.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aluminium</td>
<td>0.0650</td>
<td>1,591.98</td>
<td>InvestmentMine</td>
<td>103.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nickel</td>
<td>0.0400</td>
<td>8,060.00</td>
<td>InvestmentMine</td>
<td>358.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lithium carbonate</td>
<td>0.0300</td>
<td>2,020.00</td>
<td>OilPrice</td>
<td>180.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cobalt</td>
<td>0.1750</td>
<td>23,800.00</td>
<td>InvestmentMine</td>
<td>5,865.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel/ Iron</td>
<td>0.2000</td>
<td>300.00</td>
<td>Quandt</td>
<td>61.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polymer</td>
<td>0.1333</td>
<td>0.000186</td>
<td>Plante News</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electricity (in kWh)</td>
<td>0.1500</td>
<td>0.33</td>
<td>Statista.com - Europe</td>
<td>526.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water</td>
<td>0.1500</td>
<td>1.33</td>
<td>Water Cost Index - Global</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soda ash</td>
<td>0.0500</td>
<td>25.00</td>
<td>ICIS</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO2e</td>
<td>0.5888</td>
<td>55.48</td>
<td>The World Bank</td>
<td>3,287.65</td>
</tr>
</tbody>
</table>

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 CO$_{2}$eq, 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](image)

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.
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

<table>
<thead>
<tr>
<th>Company</th>
<th>Benefit (US$m/metric ton)</th>
<th>Environmental Effect (Person-Equivalent)</th>
<th>Ratio - Profit PE (E/1)</th>
<th>Recycling Efficiency (RE)</th>
<th>Legislation RE = 50 % (YES/NO)</th>
<th>Source</th>
<th>Lithium Recycling (YES/NO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>379.37</td>
<td>100.47</td>
<td>308.46</td>
<td>100.10</td>
<td>41.63</td>
<td>0.61</td>
<td>0.35</td>
</tr>
<tr>
<td>Company 4</td>
<td>295.05</td>
<td>1.05</td>
<td>0.78</td>
<td>YES</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Company 1</th>
<th>Company 2</th>
<th>Company 3</th>
<th>Company 4</th>
<th>Company 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Generation</td>
<td>Electricity Generation</td>
<td>Electricity Generation</td>
<td>Electricity Generation</td>
<td>Electricity Generation</td>
</tr>
<tr>
<td>Cryogenic Cooling</td>
<td>Landfilling Gypsum</td>
<td>Landfilling Residues</td>
<td>Landfilling Residues</td>
<td>Shredding Emissions</td>
</tr>
<tr>
<td>Shredding Emissions</td>
<td>Landfilling Residues</td>
<td>Disposal Wastewater</td>
<td>Disposal Wastewater</td>
<td>Furnace Waste</td>
</tr>
<tr>
<td>Landfilling Residues</td>
<td></td>
<td>Incineration of Plastics</td>
<td></td>
<td>Landfilling Residues</td>
</tr>
<tr>
<td>Disposal Wastewater</td>
<td></td>
<td></td>
<td></td>
<td>Landfilling Sulfuric Acid</td>
</tr>
</tbody>
</table>

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

120
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](image)

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.

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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:

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Company 2:

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Company 3:

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Company 4:

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Company 5:

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Company 6:

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The Company has developed a novel process for mixing lithium carbonate and other battery materials. The process was given a grant in 2003 by the U.S. Department of Energy (DOE) to scale-up the process at pilot scale. Company has demonstrated low capital cost and high energy efficiency in processing. The process is designed to be modular and scalable, allowing for the addition of new capacity as demand grows. The process includes a series of mechanical processes, in which the feed is mixed and subjected to high-energy impact mills, to break down the feed into smaller particles. The process is designed to be energy-efficient and environmentally friendly, with low greenhouse gas emissions and no significant water usage. The process is also designed to be flexible, allowing for the addition of new materials as the market evolves. The process is currently being scaled up to pilot scale, and the Company is looking for potential partners to help bring the technology to market. The Company is already working with several partners on pilot-scale projects, and expects to begin commercial production in the next few years. The Company is also actively seeking additional investors to help finance the development and commercialization of the technology.
Company 2:

The process starts with basic lithium-ion batteries, including cathode and anode battery types. The process uses a combination of pressure and thermal treatment steps to produce lithium carbonate. The battery sludge is then heated by melting, magnetic separation, and then separated into various fractions. The process is then followed by a detection stage using a temperature sensor. The temperature of the sludge is then adjusted, and the lithium carbonate is then separated into fractions. The separated fractions are then dried and packaged for further use. The entire process is monitored using a computer system to ensure quality control. The final product is then shipped to customers worldwide for use in various applications. The process is environmentally friendly and reduces the amount of waste sent to landfills.

References:

1. United States Patent 12,314,322
2. Lithium Battery Manufacturing 12,315,522
3. Company 2, 2012
Company 3:

<table>
<thead>
<tr>
<th>Name</th>
<th>Reference</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>George Macchia, T., Trefil, S., Wycky, A., Neigh, L., &amp; Hebel, M. (2012).</td>
<td>The company 3 mainly uses a mechanical processing plant for Li-ion battery waste. The batteries are crushed in a CDP gas atmosphere. The battery waste is disassembled and the cathode material is collected as non-usable components. The subsequent material separation is done and the different materials fractions are sold and/or recycled in material recyclers.</td>
<td>1-10.</td>
</tr>
<tr>
<td>Birket, A., Späle, C., Von der Linden, A., &amp; Marsch, K. (2020).</td>
<td>The process has been developed for the first time with a specified amount of lithium battery waste for environmental protection. Waste management, C2020-322, 1-20.</td>
<td>1-10.</td>
</tr>
<tr>
<td>Valdivia, D. C. (2020). Prospective environmental assessment of lithium recovery in battery recycling.</td>
<td>In the context of the paper (Zenger, et al. 2009) it is described that the recycling method deployed by Lithium is capable of processing: portable lithium-ion cells and batteries from an existing battery pack. The process description states that: however, despite any information on conditions for processing which are described, no information about the process is provided. The process flow chart illustrate the following: a) the process is limited to the treatment of lithium-ion batteries used in electric vehicles; b) the process is limited to the treatment of lithium-ion batteries used in electric vehicles; c) the process is limited to the treatment of lithium-ion batteries used in electric vehicles.</td>
<td>1-10.</td>
</tr>
<tr>
<td>DEC 2014 Environmental Impact Management of End-Of-Life Li-Ion Batteries from Electric Drive Motor Vehicles in North America.</td>
<td>The treatment of lithium batteries used in electric vehicles is described. The process flow chart illustrates the following: a) the process is limited to the treatment of lithium-ion batteries used in electric vehicles; b) the process is limited to the treatment of lithium-ion batteries used in electric vehicles; c) the process is limited to the treatment of lithium-ion batteries used in electric vehicles.</td>
<td>1-10.</td>
</tr>
<tr>
<td>Dahl, B. (2009). Battery Waste Management Life Cycle Assessment.</td>
<td>The process is an alternative process to the Li-ion batteries, where the main safety concern is to recycle the highly flammable lithium waste. The process is shown diagrammatically in Figure 3.</td>
<td>1-10.</td>
</tr>
</tbody>
</table>
Company 4:

...
The process involves a container-like piece and a hydrophilic/biological recycling process to separate Li and NaHFe batteries. The former regulates the temperature of the container, while the latter regulates the recycling temperature. The container is made of a material that can withstand high temperatures and pressures. The recycling process uses a combination of chemical and biological methods to recover valuable metals and compounds. The Li and NaHFe batteries are then separated based on their different physical properties. This process is designed to be efficient and sustainable, with a high yield of valuable materials.

The process described in the document is a single-faceted, multi-stage recycling method for lithium and lithium-ion batteries, as well as other battery types. The process involves the use of a separator, a series of batteries, a series of filters, a series of reactors, a series of pipes, and a series of temperature controllers. The system is designed to be scalable and adaptable to different battery types and sizes. The overall goal is to maximize the extraction of valuable materials from waste batteries and minimize the environmental impact of battery waste.

The process described in the document is a multi-stage recycling method for lithium and lithium-ion batteries, using a separator, a series of batteries, a series of filters, a series of reactors, a series of pipes, and a series of temperature controllers. The system is designed to be scalable and adaptable to different battery types and sizes. The overall goal is to maximize the extraction of valuable materials from waste batteries and minimize the environmental impact of battery waste.

The process involves a container-like piece and a hydrophilic/biological recycling process to separate Li and NaHFe batteries. The former regulates the temperature of the container, while the latter regulates the recycling temperature. The container is made of a material that can withstand high temperatures and pressures. The recycling process uses a combination of chemical and biological methods to recover valuable metals and compounds. The Li and NaHFe batteries are then separated based on their different physical properties. This process is designed to be efficient and sustainable, with a high yield of valuable materials.

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Company 5:


During pre-treatment the Li-ion battery pack is dismantled and the single battery cells are loaded onto a conveyor belt. The battery packs are then shredded to release the valuable materials. A fraction of the shredded material is sent to a magnetic separator to remove ferrous metals. The remaining material is then sent to a shredder to further reduce the size of the particles. The shredded material is then sent to a cyclone separator to remove larger impurities.

The final product is then sent to a series of steps to recover the valuable materials. The process is illustrated in Figure 1. The recovered materials can be used in a variety of applications, including the production of new batteries, metals reuse, and other applications.

Figure 1: Lithium process chemistry: Resources, elements, phases, and recycling. Overview.
### Appendix C – Comparison Matrix

<table>
<thead>
<tr>
<th>Groups/Parameters</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<th>H</th>
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<th>J</th>
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<tr>
<td>Technical Features</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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</tr>
<tr>
<td>Functional Features</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>Cost</td>
<td>Low</td>
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<tr>
<td>Availability</td>
<td>24/7</td>
<td>10/12</td>
<td>8/10</td>
<td>24/7</td>
<td>10/12</td>
<td>8/10</td>
<td>24/7</td>
<td>10/12</td>
<td>8/10</td>
<td>24/7</td>
<td>10/12</td>
<td>8/10</td>
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<tr>
<td>Support</td>
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<td>Good</td>
<td>Average</td>
<td>Excellent</td>
<td>Good</td>
<td>Average</td>
<td>Excellent</td>
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<td>Average</td>
<td>Excellent</td>
<td>Good</td>
<td>Average</td>
</tr>
</tbody>
</table>

Legend:
- Yes: Available
- No: Not Available
- NA: Not Applicable
- Values indicate different levels of performance.
Appendix D – Umberto NXT LCA Data
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