Title: Design of a systematic value chain for lithium-ion batteries from the raw material perspective

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Abstract:

Lithium-ion batteries are gaining a pivotal role in the envisaged energy transition of the 21st century. This development causes an increasing interest in battery raw materials such as lithium, nickel or natural graphite. The aggregation of raw-material related steps usually occurs along the upstream value chain of lithium-ion battery cell components. As this does not reflect the actual value creation, raw material-related characteristics and features are often displayed inaccurately and superficially. This paper introduces an integrated definition of value chain stages from the mineral deposit to the production of battery cell components. These value chain stages are exemplary outlined for lithium, nickel and natural graphite synthesis routes. A broad implementation of the proposed definitions facilitates the joint analysis of lithium-ion technology and raw materials by helping to improve collection and quality of data. Life cycle assessments, sustainability analysis or criticality reviews comprise exemplary fields of application.

Key Words: Battery Raw Material, Lithium-Ion-Battery, Value Chain, Supply Chain, Mineral Economics

JEL: L72, Q31, Q41, Q42, L23, L62

1. Introduction

Current energy and climate policy targets require the global decarbonization of all economic sectors (UNFCC, 2015). Both renewable energies and electromobility are considered main features for the successful realization of a carbon-free economy (European Commission, 2012; IEA, 2017). The need for sufficient energy storage options emerges from vehicle electrification and intermittent electricity generation (Conolly, 2010; Naish et al., 2008). Electrochemical storage in the form of rechargeable lithium-ion batteries currently represents the most favorable technological solution for applications such as electric vehicles or stationary storage systems (Scrosati et al., 2011; Thielmann, 2016).

The concept of industrial value chains introduced by Porter (1985) constitutes an organizational view of systems and subsystems, which implement inputs, transformation processes and outputs. These are always associated with the "acquisition and consumption of resources". Such resources are being addressed from an economical point of view (Porter, 1985). In its most basic design, raw materials are primary inputs which are transformed to final products along the value chain (Pil and Holweg, 2006). Value chain concepts are commonly associated with a non-linear perspective, thus postulating value creation through cross-sectional consideration of different value streams (Holweg and Helo, 2014). This point of view is particularly required for raw-material related considerations of value chains, as these are usually not structured linearly and incorporate interlinkages on different levels (Frenzel et al., 2017; Pietrobelli et al., 2018).

The value chain of a lithium-ion battery is already defined down to the cell production level (Pettinger et al., 2018). Nevertheless, the practical diversity of lithium-ion technology is very large. This diversity is not limited to design or size, but mainly expressed by the range of material combinations that can be used for the cell (Lamp, 2018; Nishio and Nobuhiro, 2011). When addressing the cathode for example, at least five different chemical compounds are commonly available (Andre et al., 2015; Stan et al., 2014). These are based on lithium iron phosphate (LFP), lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel cobalt aluminum oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). On the cathode side, the trend is aiming towards a reduction of the cobalt content and an increase of the manganese or nickel content. Single cathode chemistries can again be subdivided in detail, which results in numerous possibilities for different chemical structures (Andre et al., 2015; Scrosati and Garche, 2010; Zubi et al., 2018). Some applications also require a specific cathode chemistry, which may account for certain material exclusions (Marom et al., 2011). Material-related alternatives for the anode, electrolyte and separator are also expected to diversify due to related research advances (Erickson et al., 2014; Scrosati et al., 2011). Currently, natural or artificial graphite is predominantly used on the anode side as well as a small amount of silicon. Research and industry stakeholders are working intensively to increase the proportion of silicon in the anode in order to increase capacity. Separators consist of polypropylene and polyethylene and are partially coated with ceramic. The electrolyte typically mainly consists of carbonate solvents, lithiumhexafluorophosphate ($LiPF_6$) as a conducting salt and additives (Kwade et al., 2018). A new approach on a laboratory scale is the use of solid state electrolytes instead of liquid electrolytes (Zubi et al., 2018). Considering the increasing growth rates of battery applications, major impacts on several raw material markets are thus expected (Buchert et al., 2019; Eddy et al., 2018; Gielen et al., 2016; Lebedeva et al., 2017; Martin et al., 2017; Novinsky et al., 2014).

With a share of approximately 58 %, battery cell materials have the greatest influence on costs of lithium-ion battery cells (Bernhart, 2014). At the same time, the materials decisively determine the performance, life, safety and other quality parameters of the cell (Graf, 2018; Pinkwart and Tübke, 2011; Woehrle, 2018). Thus, the properties as well as the costs are substantially determined in the upstream value chain. Publications addressing sustainability issues of lithium-ion batteries and its materials further emphasize the relevance of underlying raw materials (Buchert et al; Peters et al., 2017; Schmidt et al., 2016). Especially metallic raw material extraction and processing are major contributors to the environmental burden of the anode production. Here especially greenhouse gas emissions are the main category of impact (Notter et al., 2010; Oliveira et al., 2015). Supply risks as well as social aspects also contribute significantly to sustainability issues (Reuter, 2016). In total, raw materials are of great significance for the lithium-ion technology and for the future energy supply on various levels (Eddy et al., 2018; Wellmer et al., 2019).

The need for interdisciplinary and comprehensive value chain considerations focusing on raw materials has been shown in several publications with diverse scopes (Eddy et al., 2018; Fleury and Davies, 2012; Frenzel et al., 2017; Helbig et al., 2017; Olivetti et al., 2017). However, raw material related considerations of value chains are still characterized by a comparatively low level of detail (Drielsma et al., 2016). Any phases preceding the cell component production are most commonly delineated as one single stage (Hettesheimer et al., 2013; Michaelis and Egerer, 2017). Furthermore, extraction and processing are aggregated and defined as *Raw* or *Basic Material Stage* (Lebedeva et al., 2017; Petri, 2015; Schmuch et al., 2018). Only few publications specify on different production routes or processes for raw materials within the context of lithium-ion technology (Olivetti et al., 2017; Schmidt et al., 2016; Schmuch et al., 2018; Swain, 2017). Benchmarking the value chain stages with certain indicators remains difficult for battery raw materials. The importance of improving availability and quality of data, specifically addressing battery raw material mining and processing, is inherent (Handley, 2018). In total, there is a lack of holistic approaches addressing materials and respective value chain stages specifically for lithium-ion battery cells. As opposed to this, the alliance of formerly independent industries, i.e. mining and automotive battery cell production, leads to a new value chain conception and research within this area is required (Eddy et al., 2018; European Commission, 2018, 2019a, 2019b; Handley, 2018; Olivetti et al., 2017). Therefore, this work aims at establishing a value chain classification for lithium-ion battery raw materials. This includes the determination of a distinct nomenclature for associated stages and relevant products from a mineral resources perspective.

Furthermore, the goal is to exemplary depict the proposed value chain model for battery raw materials. Lithium, cobalt, nickel, graphite and manganese comprise the main battery raw materials (European Commission, 2018). Lithium is indispensable for the functioning of the underlying battery technology. Thus, lithium from continental brines is one of three addressed battery raw materials. To cover battery raw materials necessary both for the anode and the cathode of a battery, nickel (relevant for certain cathode chemistries) and graphite (relevant for the anode coating) are exemplary addressed. Although synthetic graphite is also used for anode coatings, the scope of this work lies on natural graphite due to its current relevance as a mineral battery raw material. This is in accordance with several publications in this field (cf. Marscheider-Weidemann et al., 2016; Reuter et al., 2014). As already described above, the nickel content in battery cell chemistries is expected to increase. Thus, the selection of nickel is motivated with the expected increasing impact and significance of lithium-ion technology for nickel's value chain as a battery raw material (Campagnol et al., 2017; Gunn et al., 2018; Olivetti et al., 2017). Furthermore, in contrast to several publications addressing cobalt and manganese as a battery raw material (cf. Ahmed et al., 2017; Azevedo et al., 2018; Biswal et al., 2015; Zheng et al., 2018), there is a need for more detailed analysis of nickel production routes for lithium-ion technology (Schmidt et al., 2016). Nevertheless, it is highly intended to provide a transferable approach for analysis of other battery raw materials or raw-material sensitive future technologies (Wellmer et al., 2019). With this, the three depicted battery raw materials comprise examples to demonstrate the proposed value chain classification.

In management economic concepts, value chains in its most simple form encompass a vertical dimension and a horizontal dimension (Holweg and Helo, 2014). The vertical dimension covers numerous steps related to one certain product. The horizontal dimension relates to one stage along different parallel value chains. Main purpose of the methodology for this work is to enable the vertical design of the value chain followed by horizontal exemplification for three battery raw materials. As inherent to all generic classification approaches, covering a vertical value chain architecture is always prevalent to in-depth analysis of single steps. Concerning the general concept of value chains, it is noteworthy that the term *value chain* is often used synonymously with the term *supply chain* (Rainbird, 2004). As the term supply chain commonly incorporates linear flows between different stages (Holweg and Helo, 2014), the associated concept is not considered suitable for illustrating the multifaceted aspects of battery raw material market dynamics. In the same sense, the typically associated focus on *management* of supply chains (Beamon, 1998) is not within the scope of this study. In fact, the proposed concept of *value grids* (Pil and Holweg, 2006) could constitute a logical next step for a deeper analysis.

Especially when adopting a broad, battery raw material-driven perspective, generic concepts seem to be rare. One publication specifically addressing prominent issues along the supply chain of automotive lithium-ion batteries could be identified (Egbue and Long, 2012). However, the main purpose of that work lies on the identification of critical issues and characterization of benchmarking factors along the lithium supply chain. Thus, the underlying methodologies mainly focus on literature review analysis (Charvet et al., 2008) and framework development for investigating relevant factors along the supply chain (Butler et al., 2006). As the aim of this work focuses on a more holistic, overarching architectural approach, the before mentioned methodologies are only of limited benefit.

From a general point of view, Kaplinski and Morris (2001) propose a detailed methodology for value chain research based on a diverse range of *issues*. These can be considered differently depending on the individual research project. All issues need to be regarded under the premise of the final market, which are automotive lithium-ion battery cells for the present study. By considering such issues relevant for value chain research already for the classification of the value chain, the concept proposed by Kaplinski and Morris (2001) is reversed. Therefore, subsequent analysis is facilitated as necessary aspects are already included and the value chain is structured accordingly.

The approach on hand focusses on the uniform consideration of battery raw material value chains. By introducing a conclusive nomenclature and a consistent classification, the depiction, analysis and assessment of raw material value chains for lithium-ion technology is facilitated. Possible improvements can be achieved among market analysis, life cycle assessments, criticality evaluations or sustainability reviews. Thus, by applying an approach under consideration of a cross-sectional framework, mutual understanding between the mineral industry and battery producers is supported and enhanced.

2. Methods

The methodological approach aligns with the targets of this work. First, the introduction of an appropriate nomenclature and the associated value chain architecture requires outlining the methodology for setting up definitions accordingly. Second, applying the newly defined value chain concept also requires a methodological approach. Finally, a corresponding survey conducted by the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen is described in terms of its relevance for this work.

In total, Kaplinski and Morris (2001) identify eight relevant issues for conducting value chain analysis, of which seven are considered relevant for the present study (cf. Figure 1). In-line with the aim of this study, these issues are assigned either to the definition or to the exemplification of the value chain. As such, the respective issues are discussed in the following sections. The selected methodology's scope lies beyond company-level analysis and on international economic-level.

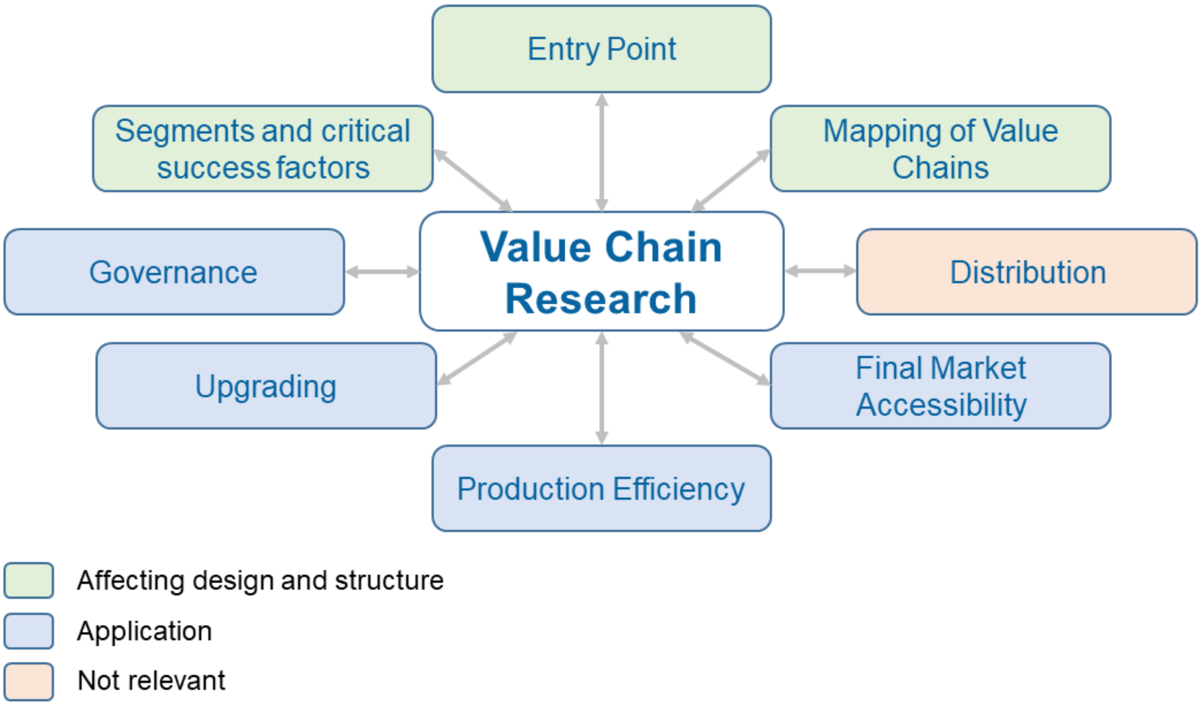


Figure 1: Eight issues for conducting value chain research as methodological basis (modified after Kaplinsky and Morris, 2001)

2.1 Definitions

The first step comprises the set-up and definition of value chain stages and the associated architecture. For the definition of the terminology, the Dictionary of Mining, Mineral, and Related Terms published by the American Geological Institute was used (American Geological Institute, 1997). As outlined in Figure 1, the following three issues affecting the design and structure of the value chain are considered (Kaplinsky and Morris, 2001):

- Entry point
- Mapping of value chains
- Segments and critical success factors

From the point of entry at exploration company level, the mining, processing and refining enterprises all the way up to the n-tier suppliers are relevant. Any stakeholders being traders, buyers or other downstream-related points of entry are not considered. Mapping and structuring of value chains focus on the physical flow of commodities. Thus, the system boundary for definition and analysis constitutes the primary raw materials perspective. Accordingly, the classification only comprises stages where raw material changes occur. With these being naturally located upstream along the value chain, typical downstream-activities such as sales, services or distribution are not part of the study. Recycling or any other secondary raw material stream is also not considered. The segmentation of relevant markets constrains the value chain setup by considering the intersection of relevant technologies, i.e. lithium-ion batteries, and commodities, i.e. battery raw materials. Thus, critical success factors relate to raw material requirements, as these are especially relevant for the lithium-ion technology.

2.2 Application

For the application of the theoretical value chain concept, each newly defined stage and the corresponding steps are exemplary outlined. The addressed battery raw materials comprise lithium brines, nickel ores and natural flake graphite. As described above, the selection originates from the purpose to demonstrate applicability based on battery raw materials with varying properties. For this purpose, the following five issues from Kaplinski and Morris (2001) focusing on the analysis of the value chain are considered:

- Final market accessibility
- Production efficiency
- Governance
- Upgrading

As the depiction of the value chain mainly serves the purpose of validation and proof of application, the abovementioned factors are not subject to in-depth evaluation. In terms of any quantified assessment of raw materials markets (e.g. production volume, resources, reserves), data provided by the United States Geological Survey (USGS) was used to ensure consistency. Regarding the final market accessibility, the relevant markets are characterized either as *buyer-driven* or as *producer-driven*. Production efficiency is quantified in terms of recovery yields on the respective value chain stage. Governance issues are addressed by stating criticality of the respective raw material based on the European Union's list of critical raw materials (Mathieux et al., 2017). Upgrading is addressed by illustrating implemented or planned practices within the value chain leading to an increase in performance of the respective products. The issue of distribution, which is also part of the methodology proposed by Kaplinski and Morris (2001) is not considered as relevant. This is due to its largely quantitative orientation on income-related components of the value chain, which are beyond the scope of this study.

2.3 Survey

The issue of designing process routes for lithium-ion battery cell components was part of a survey conducted by the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. The questionnaire is available in the additional material. In total, 53 participants took part of which 36 are associated with the industry and 17 are associated with research institutions. Several questions were related to the lithium-ion battery cell value chain and upstream activities. Regarding transparency and knowledge of the battery cell value chain, 68 % of the participants indicated that they are not familiar with the entire value chain. This was related to underlying processes as well as intermediate and final products. The importance of upstream value chain activities for performance improvements of the battery cell was indicated at least "increasing" by 83 % of all participants. The importance of upstream value chain activities for reducing cell production costs was indicated at least "increasing" by 85 % of all participants. On the one hand, this underlines the above mentioned need to define value chain stages specifically for lithium-ion battery cells. On the other hand, the gap regarding raw materials and processes is outlined again, not only from an academic point of view but also from an industry's perspective.

3. Results

3.1 Overview

The aggregation of process steps is commonly performed by a single company or at a single location within a value chain. The defined structure of the material related part of a value chain encompasses four major stages, namely Raw Material Stage, Intermediate Material Stage, Product Material Stage and

Tier-n-Stage (cf. Figure 2). The definition of each stage is illustrated in the following sections and directly specified with the practical application. These four stages, hence at least one step of each stage, occur independently of the considered final product and the initial material. Thus, the occurrence (and the sequence) of each single step within a stage varies concerning individual material requirements. The resulting stage of the value chain after the Tier-n-Stage is the Product Stage, where the production or assembly of the final product takes place. Figure 2 does not show the final Product Stage because raw material related considerations predominantly affect only the depicted stages. In addition, the Tier-n-Stage is the first stage not having a material as final product.

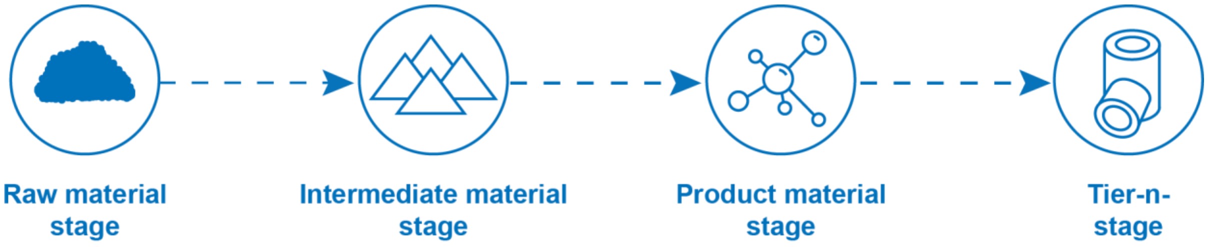


Figure 2: Overview on defined value chain stages

Besides a general description of the defined value chain stages, the illustration of varying configurations within these stages requires specific examples. Hence, precise steps and processes for the production of the active material of the positive and negative electrode are depicted additionally. This encompasses the preparation of lithium from continental brines, nickel out of laterite ores and natural graphite with specific focus on flake graphite.

3.2 Raw Material Stage

The Raw Material Stage comprises all activities associated with a mining operation. In general, a raw material is defined as a material that can be further processed and is converted into a final product (American Geological Institute, 1997). Derived from this definition, the origin of the Raw Material Stage is the deposit material. The deposit material is defined as the natural occurrence of a mineral raw material in economic quantity and quality for mining. This encompasses any form of mineral deposits including brines and ores. Derived from the mining definition of the American Geological Institute (1997), the material passes the steps exploration, extraction and beneficiation.

Naturally accompanied with initial investments and a first encounter with the environment, exploration is crucial for the evaluation of a mineral raw materials' value chain (ELAW, 2010). Furthermore, a proactive availability planning for mineral raw materials is dependent on the consideration of exploration, as the time from discovery to production increases steadily (Ericsson et al., 2017). As a key component, extraction relates to all forms of exploiting the deposit by surface, underground or solution mining. Dressing within the Raw Material Stage can refer to size regulation, sorting and classification. In any case, the associated processes along all stages do not modify the material chemically. Thus, this stage ends up with the production of a concentrate material (cf. Figure 3). For mineral commodities, this product is commonly referred to as mine production.

Figure 3: Raw Material Stage

3.2.1 Raw Material Stage: Lithium

Pegmatite and continental brines constitute the most important deposit materials for lithium. Additionally, some geothermal and oil field brines as well as clay minerals are potential lithium sources (Wietelmann and Steinbild, 2014). Main mining countries are Australia for pegmatite as well as Chile and Argentina for brines (Jaskula, 2018). Due to the intertwined nature of lithium brine processing, it is not possible to differentiate production figures between the Raw Material Stage and the Intermediate Material Stage. Approximately 78 % of the world's lithium reserves (Rongguo et al., 2016) and 53 % of the worldwide lithium supply currently originates from continental brines (Andrews et al., 2016). However, any quantitative statement of lithium resources and reserves needs to be interpreted carefully. This is due to the fact that only a minority of lithium deposits are reported according to CRIRSCO standards (e.g. JORC or NI 43-101), which leads to considerable variations (Christmann et al., 2015). The acronym CRIRSCO relates to the "Committee for Mineral Reserves International Reporting Standards", which publishes reporting standards for mineral deposit estimates of its member countries.

The production of a lithium concentrate from continental brines requires two major steps. The first step requires braking or drilling the crust of the salt brine. Then the brine has to be pumped into evaporation ponds. In the course of an evaporation procedure, halite (NaCl) and other salts are then precipitated in sequence in several steps within changing ponds. Solar evaporation itself is highly weather-dependent and characterized by low recovery rates of around 50 % (Choubey et al., 2016). Eventually a Li content of 6 % in the concentrate is needed to process a high purity lithium carbonate for the lithium-ion battery cell production (Garrett, 2004; Tran and Luong, 2015). Apart from sulfates, the amount of magnesium influences the effort necessary to extract and concentrate lithium from brines (Gruber et al., 2011). A low amount of magnesium is favorable, as impurities can be directly removed through evaporation enabled by solar radiation (Vikström et al., 2013). Otherwise, pretreatment is necessary to avoid subsequent coprecipitation of impurities with lithium (Averill and Olson, 1978).

3.2.2 Raw Material Stage: Nickel

Laterite nickel deposits represent 60 % of the worldwide land-based nickel resources, whereas sulphidic nickel deposits constitute the remainder (McRae, 2018). For the current supply situation, a comparable distribution is assumed with steadily increasing production from laterites (Butt and Cluzel, 2013). Increased production from laterite ores leads to a larger environmental impact due to more complex processing technologies (Mudd, 2010). In total, worldwide mine production amounts to 2,160,000 t, with major mining countries being the Philippines, Indonesia, New Caledonia, Canada and Russia (McRae, 2019). Compared to lithium and natural graphite, the variety of producing countries on the Raw Material Stage is much more diverse. Currently the European Union does not consider nickel as a critical raw material (Mathieux et al., 2017).

Residual deposits like laterite ores arise from weathering near the surface. Owed by the genesis, laterite ores are characterized by shallowness and a tender material constitution (Neukirchen and Ries, 2014). Laterite nickel ores are further subdivided into limonites and saprolites. Different processing methods are required due to the different constitutions of these ores (Schmidt et al., 2016). Laterite deposit characteristics usually enable the ore extraction in an open pit operation by removal of a relatively thin layer of overburden (Marsh et al., 2013). Additionally, the weathered deposit material frequently allows a material extraction without blasting (Clow, 1992). The economic nickel content in laterite ores typically lies between 0.9 % and 3 % (Bide et al., 2008). To generate a nickel concentrate, in a first step the extracted ore is downsized by gentle crushing or grinding. Afterwards, using screens, spiral classifiers and hydrocyclones the small, soft, nickel-rich particles are separated from large, hard nickel-lean particles. Contemporary beneficiation plants generate concentrates from limonites with nickel contents up to twice of the deposit material content (Crundwell et al., 2011).

3.2.3 Raw Material Stage: Natural Graphite

With amorphous, lump and crystalline flake graphite, three main types of natural graphite can be identified, of which almost all exclusively result from organic material subject to metamorphism (Krauss et al., 1988). Nevertheless, high-purity flake graphite is preferable for lithium-ion battery anode material due to its advantageous characteristics (Wissler, 2006). Thus, to a certain degree the usability of natural graphite deposits for lithium-ion battery material is already predetermined on the Raw Material Stage. More specifically, the final natural graphite-based precursor material for lithium-ion battery anodes requires two main prerequisites (Hatch, 2014; Steinrötter, 2011). First, a purity exceeding at least 99.9 % carbon-as-graphite (Cg) with no metal impurities is necessary. Second, an average particle diameter between 10 μm and 30 μm in combination with advantageous particle geometry is required. Both purity and size requirements are necessary to maintain high electrical conductivity as anode material (Li et al., 2011a).

Flake graphite consists of flat, plate-like particles accumulated as layers, pockets or lenses within strata bound deposits. An average grade of Cg varying between 2 % and 30 % characterizes associated ore bodies (Taylor, 1994). Already at the exploration step of such flake graphite deposits, six key factors are relevant to understand if the possibility to process battery grade graphite exists (Scogings et al., 2015): Deposit size and contained graphite, location and logistics, flake size distribution, offtake agreement, timeframe to production and product purity. After conventional extraction of flake graphite mainly from surface deposits, mechanical separation by crushing and grinding follows (Lämmerer and Flachberger, 2017). The creation of a high-grade flotation concentrate with at least 95 % Cg is inevitable as next step of dressing, for which only medium, large and extra-large flakes are best suited as input material. The last step of dressing at the Raw Material Stage includes drying and sorting the wet material coming from flotation (Chehreh Chelgani et al., 2015). Future technological advancements include electrodynamic fragmentation in the field of crushing and grinding as well as triboelectric conveyor belt sorting (Lämmerer and Flachberger, 2017).

Worldwide reserves of natural graphite are estimated at 300,000,000 t in 2017. The overall mine production of natural graphite accounted for around 900,000 t in 2017 (Olson, 2019). China dominates the Raw Material Stage with a share of around 70 %. Thus, mainly due to its high supply risk, natural graphite is considered as a critical raw material for the European Union (Mathieux et al., 2017). Concerning flake graphite, the available market data is very limited.

3.3 Intermediate Material Stage

The second stage in a battery material value chain is defined as the Intermediate Material Stage. In general, the term "intermediate" is defined as "coming between two things" (Oxford University Press, 2010). With the material being subject to further processing, but still on a rather application-independent level, this generic term is most suitable. The concentrate material derived from the Raw Material Stage constitutes the feedstock material for this stage. Depending on the type of concentrate material, the steps smelting, purification or refining can be implemented (cf. Figure 4). Smelting refers to the metallurgical operation typically applied for chemical reduction of metal from its ore (American Geological Institute, 1997). Thus, the Intermediate Material Stage is always associated with a chemical modification of the material. The purpose of the Intermediate Material Stage is to produce a precursor material, which meets all qualitative or chemical requirements to be readily usable for the third step. For metals from the group of mineral commodities, this product is commonly referred to as refinery production. The precursor material as a product of the Raw Material Stage is not available as a usable form for the final application. The processes at this level are not necessarily product specific and are covered by typical mining or chemical companies. In parts, both levels can be served by the same company or by separate companies.

Figure 4: Intermediate Material Stage

3.3.1 Intermediate Material Stage: Lithium

Regarding processing of lithium deposits, the applied technique differs significantly for brine or pegmatite deposits (Hao et al., 2017). For brine deposits, a lithium chloride solution is produced after solar evaporation. Lithium carbonate is then precipitated from the lithium chloride solution using sodium carbonate (Swain, 2017). As the amount of impurities and correspondingly the average lithium concentration differs significantly, the exact process and associated complexity is highly depending on the deposit's properties. Additionally, the type of product to be obtained also influences the implemented process (Liang and MacNeil, 2012). Due to the dependency on solar evaporation, average production rates from brine deposits vary between one and two years, although longer timescales are also possible (Vikström et al., 2013). Future advancements to recover lithium from brines focus both on new evaporitic technologies, e.g. extraction from concentrated brines, as well as non-evaporitic technologies, e.g. selective adsorption (Flexer et al., 2018).

For lithium-ion batteries, either lithium hydroxide or lithium carbonate are most frequently used for the cathode material (Martin et al., 2017). From an economical perspective, lithium carbonate is preferred, as it requires fewer production steps (Tran and Luong, 2015). From a battery technological point of view, lithium hydroxide is preferred as it decomposes at lower temperatures, which in turn leads to improved material use resulting in comparable performance. Additionally, with nickel-rich cathode chemistries, e.g. NMC 622 or NMC 811, the use of high-quality lithium hydroxide is obligatory (Matich, 2014). Nevertheless, from a sole technical point of view, both mineral and brine deposits can be considered to source lithium-ion battery material (Talens Peiró et al., 2013).

The worldwide lithium production accounted for around 69,000 t of contained lithium metal in 2017 (Jaskula, 2019). Especially when stating lithium-related figures a clear indication of the unit is crucial as a variety of lithium compounds may be used (Christmann et al., 2015). The lithium market is increasingly driven by battery industry demand (Azevedo et al., 2018), although it is currently not considered as a critical raw material by the European Union (Mathieux et al., 2017). However, with lithium recycling rates of less than 1 % and the expected increase in lithium-ion battery applications, supply for primary lithium is going to be challenged within the next decade (Kavanagh et al., 2018). This is especially aggravated as prices for lithium compounds are of secondary relevance, leaving supply security as the main issue for the lithium-ion battery industry (Jaskula, 2018).

3.3.2 Intermediate Material Stage: Nickel

Smelting, purification and refining of laterite ores is directly related to the type of mineral associated with the ore body. As both saprolite and limonite layers can be present within the same orebody, the identification and separation of the layers is necessary. The two processing routes usually implemented are the production of ferronickel through smelting (Caron process) and the production of nickel metal through leaching (i.e. purification) and refining. As limonites are associated with an iron content exceeding economical values for smelting (about 35 % Fe), limonitic ores are leached and refined. Refining losses for limonites amount to around 5 % depending on the operation. Vice versa, saprolites contain a lower iron content (about 15 % Fe) and can be smelted economically, but the associated magnesium oxide content is too high for economical leaching. Therefore, pyrometallurgical processes are ideally suited for saprolites and hydrometallurgical processes are commonly implemented for limonites. Recovery rates for pyrometallurgical operations are usually lower than for hydrometallurgical processes (Bide et al., 2008; Crundwell et al., 2011; Fisher, 2011; Hawkins, 1998). As leaching with sulphuric acid is still associated with a high environmental impact, hydrometallurgical advancements in laterite leaching focus on the use of leaching agents such as hydrochloric or organic acids (McDonald and Whittington, 2008).

The use of nickel as a precursor material for lithium-ion battery cathodes is subject to a certain degree of uncertainty (Schmidt et al., 2016). Several studies were identified which assume that nickel sulphide is used as a precursor material for lithium-ion batteries, although all suggest the production of nickel sulphide by chemical conversion from metallic nickel utilizing sulfuric acid (Buchert et al., 2011a, 2011b; Schmidt et al., 2016). Other nickel chemicals, e.g. nickel oxyhydroxide, are also identified as possible electrode materials for nickel metal hydride batteries (Bradley, 2011). Nevertheless, no publication outlining the direct production of nickel chemicals from ore is available, only the indirect production from nickel metal is indicated. It is assumed that the lack of data results from the small ratio of less than 7 % primary nickel being used for batteries, catalysts and specialty chemicals (Nickel Institute, 2016). This corresponds to a worldwide refinery production of nickel chemicals of around 15,400 t in 2015 (McRae, 2018). In general, it is assumed that all geological sources and production routes may be chosen to produce nickel products for lithium-ion battery applications. With the nickel market being still heavily buyer-driven by the stainless steel industry, a continuous shift towards emerging technologies and associated product requirements can be expected (Campagnol et al., 2017).

3.3.3 Intermediate Material Stage: Natural Graphite

As natural flake graphite concentrate material does not meet the already mentioned purity and size requirements, additional processes are inevitable. Concerning the steps outlined in Figure 4, smelting is not relevant for the production of a precursor material from flake graphite. Subsequently, a combination of thermal, chemical and specific milling processes is executed. By utilizing specific milling processes defined as micronization and spheronization, graphite flakes are rounded and minimized producing material defined as spherical graphite. Yields for spheronization and micronization processes are very low, leaving between 60 % and 70 % of the input material as extremely fine waste (Steinrötter, 2011). Spherical graphite also needs to be purified by either hydro- and/or pyrometallurgical processing to achieve purity levels exceeding 99.99 % Cg (Lämmerer and Flachberger, 2017). Common examples for hydrometallurgical refining are the hydrofluoric leach process or caustic bake process (Chehreh Chelgani et al., 2015). The process order is variable and depends on the manufacturer (Hatch, 2014). Overall, a compromise between size and purity needs to be achieved (Scogings, 2015). This leaves medium and large flake graphite as the sole feedstock for lithium-ion battery anode material, although it is reported that only medium flake graphite is used as such (BMI, 2015).

3.4 Product Material Stage

The Product Material Stage is related to the production of the actual component material. This product material is the final material needed for the prospective application. Usually, the material is not subject to further purification, but fabrication to the required chemical and physical applicative form and shape (cf. Figure 5). In contrast to the Raw Material Stage, blending and combination along different precursor materials is possible (Dunn et al., 2015).

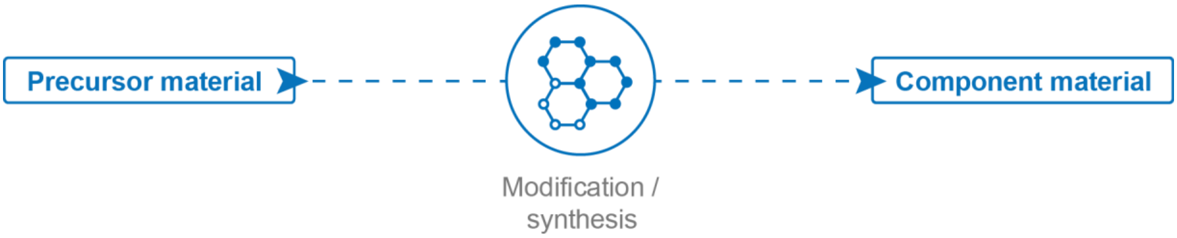


Figure 5: Product Material Stage

3.4.1 Product Material Stage: Lithium and Nickel

On the Product Material Stage, nickel and lithium cannot be regarded separately. Lithium-Nickel-Manganese-Cobaltoxide ($LiNi_xMn_yCo_{1-x-y}O_2$) is one of the most important cathode materials for lithium-ion batteries. The modification of NMC ($LiNi_xMn_yCo_{1-x-y}O_2$) can basically be divided into two major sub-stages (Wu et al., 2012) (cf. Figure 6). The first sub-stage is the preparation of a precursor (e.g. $Ni_xMn_yCo_{1-x-y}(OH)_2$) from the precursor materials (e.g. $NiSO_4$, $CoSO_4$, $MnSO_4$). In this initial step, the co-precipitation reaction is particularly important. The second step, however, encompasses all process steps for converting the precursor into the final product NMC. In principle, these are mixing, calcination and grinding processes (Ahmed et al., 2017; Wu et al., 2012).

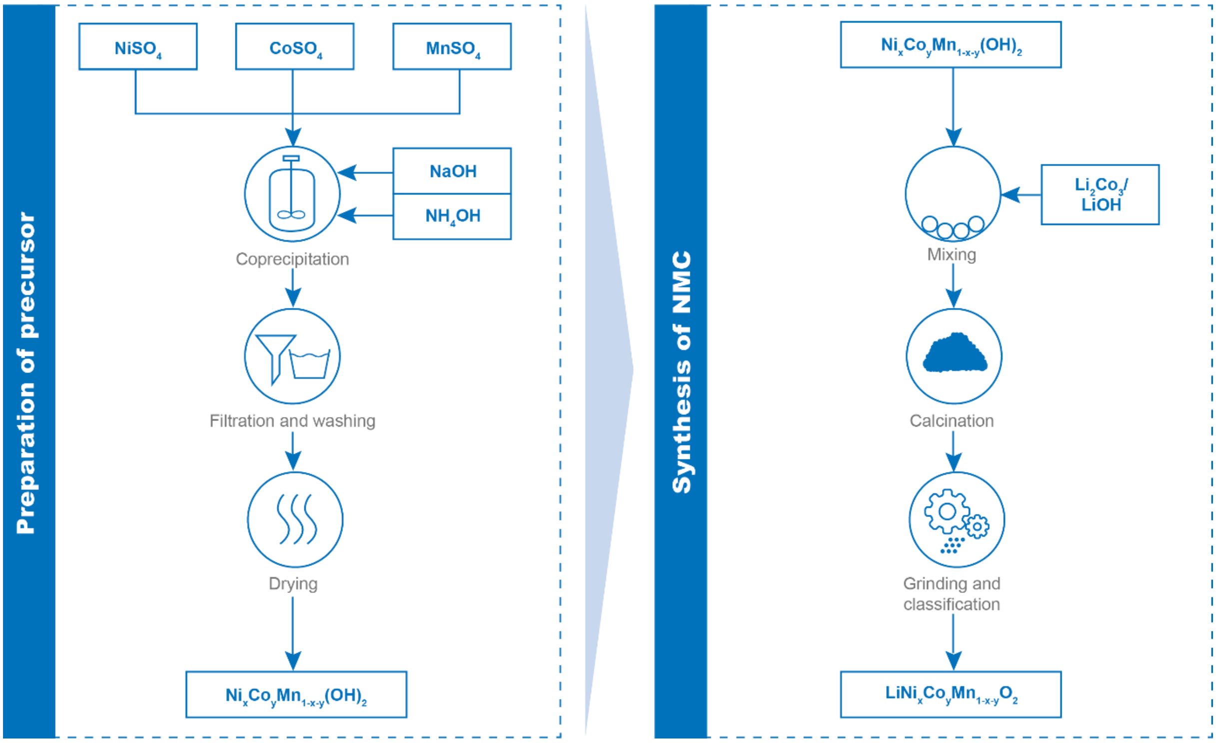


Figure 6: NMC preparation and synthesis (Ahmed et al., 2017; Wu et al., 2012)

3.4.2 Product Material Stage: Natural Graphite

The Product Material Stage for natural graphite serves to finally optimize electrochemical performance. Final modification and synthesis of the precursor material comprises conditioning, grinding, classifying and coating, which together can be summarized as particle refinement (Schmuch et al., 2018). These processes are comparable to those applied to synthetic graphite. Repeated grinding, for example utilizing impact milling or vibration-rod milling, aims to impact the materials surface for affecting lithium deposition morphology (Honbo et al., 2009). Especially the coating of the precursor material is a key process on this stage. Coating aims to create a protective layer between the actual graphite core and the electrolyte, impacting the solid electrolyte interface (Wurm et al., 2018). For this, thermal vapor decomposition (TVD) is executed to apply a carbon coating on the surface of the natural graphite precursor material (Yoshio et al., 2004). Finally, carbon-coated spherical natural graphite is produced as component material.

3.5 Tier-n-Stage

The last stage of the value chain is defined as Tier-n-Stage. The term tier is defined as “a level […] within the hierarchy of an organization or system” (Oxford University Press, 2010). In combination with the variable “n” any applicant can specify the stage (Kaplinsky and Morris, 2001). With the component material serving as feedstock material, all sub-stages producing the final cell components are implemented on this level (cf. Figure 7). Those include the production of anode, cathode, separator and electrolyte. Different to all preceding value chain stages, the Tier-n-Stage is the only value chain stage not related to a material as a product. Depending on the individual perspective, the nomination of the Tier-n-Stage can be adapted. Battery producers may relate to the Tier-n-Stage as the 1st-tier component stage, whereas automobile manufacturers may relate to this stage as the 2nd-tier or 3rd-tier component stage. It is important to consider that cell manufacturers may also cover this level themselves.

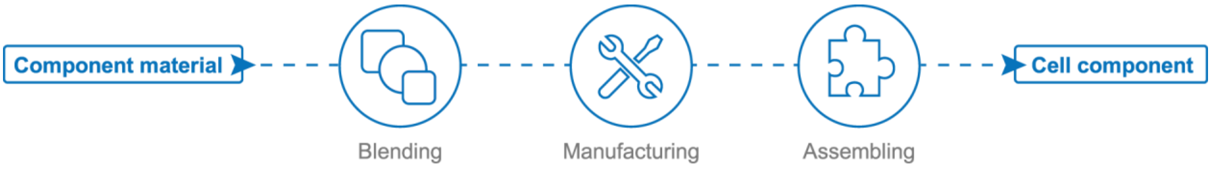


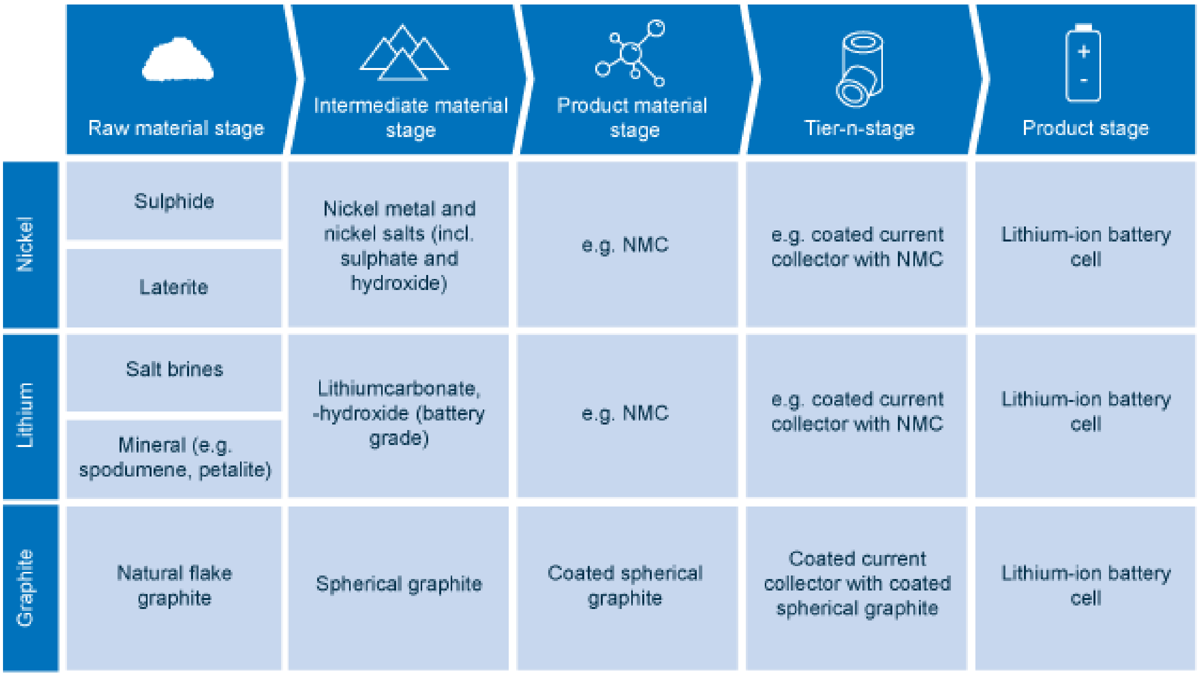
Figure 7: Tier-n-Stage

3.5.1 Tier-n-Stage: Electrode

Similar to the Product Material Stage, the assessment of separate raw and intermediate materials is not possible. Thus, the processes implemented on this stage are exemplary depicted for electrode manufacturing. The production of the electrode decisively influences the battery cell’s properties and performance. First, respective component materials for the anode and cathode are blended together with binding agents, solvents and conductive additives (Li et al., 2011a). The used solvent determines the applied method, being either water-based or organic solvent-based (Saeki et al., 2004). The produced slurry is dispersed and applied to the current collector during the coating process. For this fabrication of the electrode, a variety of technologies can be used (Li et al., 2011b). After coating and drying, a compaction process follows to reduce existing cavities. The applied coating is based on metal powder (Huang et al., 2005) or carbon materials (Cushing and Goodenough, 2002). With this, manufacturing is completed. Finally, assembling is initiated with the slitting of coils from the main coil (or mother coil) and vacuum drying to eliminate residual moisture (Pettinger et al., 2018).

3.6 Synopsis

By transferring value chain approaches from economic management concepts, four stages have been defined. These are exemplary outlined for the battery raw materials lithium, nickel and natural graphite (cf. Figure 8).



	Raw material stage	Intermediate material stage	Product material stage	Tier-n-stage	Product stage
Nickel	Sulphide Laterite	Nickel metal and nickel salts (incl. sulphate and hydroxide)	e.g. NMC	e.g. coated current collector with NMC	Lithium-ion battery cell
Lithium	Salt brines Mineral (e.g. spodumene, petalite)	Lithiumcarbonate, -hydroxide (battery grade)	e.g. NMC	e.g. coated current collector with NMC	Lithium-ion battery cell
Graphite	Natural flake graphite	Spherical graphite	Coated spherical graphite	Coated current collector with coated spherical graphite	Lithium-ion battery cell

Figure 8: Newly defined value chain classification for battery raw materials exemplified for nickel and lithium

The *Raw Material Stage* comprises sulphidic or lateritic deposits of nickel, salt brines and mineral deposits of lithium and flake deposits of natural graphite. The link to the target product is still universal on this stage, as the only product-specific differentiations are of geological nature and not implemented through further processing or treatment. The *Intermediate Material Stage* contains nickel metal and salts as well as lithium carbonate or lithium hydroxide, which are both preceding materials for the positive electrode material. Precursor material for the negative electrode is spherical graphite. The resulting final electrode materials are depicted on the *Product Material Stage*. For the material of the positive electrode, nickel-manganese-cobalt-oxide (NMC) is outlined, whereas the negative electrode consists of coated spherical graphite, possibly blended with synthetic graphite and silicon. On *Tier-n-Stage* level, the current collector is coated with the respective component material. No further change of chemical material composition is inherent to this stage. The denomination of the *Tier-n-Stage* also emphasizes the importance of the viewer's perspective, leaving the number of subsidiary stages and thus the denomination variable. The final Product Stage is related to the actual manufacturing of the battery cell based on the preceding components and materials. Again, no further chemical material change takes place on this stage. Facilitating the application of terminology even further, stages and steps are set up combinable for specific indication. Within the Raw Material Stage for example, this allows combinations such as *raw material exploration* or *raw material extraction.*

4. Discussion

With this study being located in the field of classifications and definitions, the need for discussing different subjects is inherent. Thus, the discussion is structured by addressing the value-chain related methodology, the basis of terminology and the raw-material centered concept. Finally, the overall work is assessed by means of a SWOT analysis that also outlines implications of the new concept.

4.1 Methodology

In terms of methodology, it was not possible to identify a generic approach for the new-conception and definition of value chains. Interestingly, concepts for the design of supply chains exist (Garcia and You, 2015; Nuss et al., 2015). These are usually company-level considerations, as supply chain research in general is logistics-driven. Thus, associated methodologies are also determined unsuitable for this study. The applied methodology by Kaplinski and Morris (2001) was originally intended to analyze existing company-specific value chains. Nevertheless, by reversing and segmenting the proposed methodology into definitional and analytical sections we believe to have found a valid, yet improvised approach to address the objective of this study. Benchmarking the newly defined stages and steps with associated indicators shows comparable results with (Egbue and Long, 2012), proving the applicability of the introduced methodology.

4.2 Terminology

Regarding the present topic being predominantly located in the fields of mining, metallurgy and mineral economics, a variety of disciplines are involved intrinsically (Gordon and Tilton, 2008). Implementing an emerging technology branch as part of a combined value chain classification complicates the effort to find clear and unambiguous definitions. Within the mining and minerals industry, terms and definitions are often already biased and sometimes even used differently depending on the raw material. This is the case for nickel or cobalt for example, where *intermediate material* is a specific type of already refined and market-ready product (Mudd, 2010; Piret, 1998). However, for other raw materials, *intermediate material* or *product* is defined much broader (Dewulf et al., 2010; Ebensperger et al., 2005; Tuusjärvi et al., 2014). Another example arises from the use of the term *extraction*. Whereas the mining perspective relates extraction to the removal of ore from the ground, the metallurgical perspective associates extraction to the obtainment of metal from ore, e.g. solvent extraction (American Geological Institute, 1997). Concerning the issue of geographical process localization, the boundary between the Raw Material Stage and the Intermediate Material Stage is the bottleneck. Apart from considering physical and chemical effects on the material for distinction (Taggart, 1945), processes geographically carried out at the mine site are allocated along the Raw Material Stage. This differentiation originates from economic considerations and constitutes a widespread concept in the mining and minerals industry (Subba Rao, 2011). It correlates with the definition of the Raw Material Stage, derived from an early definition of the term *primary commodity* (United Nations Conference on Trade and Employment, 1948). As such, the term refers not only to the extraction of material from the ground, but also comprises processes necessary to upgrade the material to a first market-ready product.

Furthermore, the technology-specific approach includes all relevant raw materials independent of its superior type or origin by definition, i.e. all mineral raw materials. Thus, a common foundation for defining the value chain including its stages and steps is inevitable. This leads to definitional limitations when it comes to processing steps of metallic raw materials and non-metallic raw materials for example. The influence of metals on preceding conceptual studies and approaches is vast, as several publications show (Gordon et al., 2006; Graedel et al., 2012; Nassar et al., 2015). In addition, there seems to be a tendency applying the term *materials* synonymously with the term *metals* (Graedel et al., 2015). Such generalizations are not beneficial for evaluating technology value chains relying equally on non-metallic raw materials. Whereas metallurgical terminology is hence found frequently along mining value chains (Macfarlane, 2015), non-metallurgical terminology is underrepresented. As such, non-metallurgical processes are affiliated with *mineral processing* or *beneficiation* (Chehreh Chelgani et al., 2015; Olson et al., 2016). The appropriate term *minerals engineering* (not to be confused with *minerals processing*), as translated from and used in the German language, does not seem to be popular at all on an international level. With mineral processing incorporating extractive metallurgy as one of three associated branches (Taggart, 1945), the term itself is not sufficiently applicable to non-metallic raw materials. The term *beneficiation* is also subject to ambiguous definitions, as it is synonymously used with *ore dressing* or *mineral dressing* (Rao 2011) although the respective definitions differ partially (American Geological Institute, 1997). Also, beneficiation processes are not located mandatory along certain raw material's value chains (Nickel Institute, 2016). This tightens the struggle to define appropriate yet overlapping terminology for upstream-related processes. Incorporating *dressing* as the last step in the Raw Material Stage offers an adequate solution with its explicit definition implying non-chemical changes to the material (Taggart, 1945), thus matching the definition of the associated Raw Material Stage. Proceeding, it may actually be questionable if generic definitions of terminology is achievable among such a variety of disciplines along the value chain from a scientific perspective.

4.3 Raw material centered concept

The breakdown of raw material related processes as proposed by Schmuch et al. (2018) may be useful in the sense of material science, but does not reflect common value chain structures in the raw materials industry. Especially downstream Raw and Intermediate Material Stages need to be differentiated, not only from a technical perspective but also from a market's point of view. This is of particular importance when addressing metallic raw materials with clear differences between mining and refining steps. The presented approach closes this gap by adjusting the value chain stages and steps accordingly.

With lithium brines, one deposit type of battery raw materials occurs in fluid form, whereas commonly only solid raw materials are perceived as being subject to *mining*. This is already expressed by the difficulty of defining comparable and standardized reserves and resources for lithium brine deposits (Christmann et al., 2015; Weber, 2016). Nevertheless, as already discussed above, the geographical distinction of upstream value chain steps at the mine site and off the mine site (Subba Rao, 2011) has been applied explicitly to lithium brines as well. With this, the chosen approach was developed as consistent as possible. Nonetheless, there is still a significant need for research linking the broader raw material-related value chain concept to lithium-ion technology. In particular, this is required for non-metallic battery raw materials.

4.4 SWOT analysis

The proposed classification of value chain stages offers a technology-specific approach for depicting the value chain of lithium-ion battery cells and related battery raw materials. With consistent definitions of the stages and corresponding steps, comparability both between different raw materials as well as between different routes of equal raw materials is given. This also ensures the holistic consideration of the entire value chain relevant for the technology. If necessary, the presented stages provide an overarching framework to extend subjacent steps.

However, as with every generalized approach, details can get lost. In this sense, the combined consideration of metallic and non-metallic raw materials for defining the value chain stages eventually leads to compromises. These manifest themselves especially along the definitions of the respective technical steps of the Raw and Intermediate Material Stages. For the case of this study, available data, especially for natural graphite and nickel, was limited. This of course restricts the practical validation of the concept with qualitative as well as quantitative factors.

The presented concept aims to serve as a common basis to interconnect downstream disciplines such as exploration, mining and metallurgy with upstream disciplines related to lithium-ion technology. As technology-specific differentiation criteria are shifted towards the Raw and Intermediate Material Stage, this study helps to create unambiguousness and generate transparence. By doing so, understanding of battery raw materials is improved and the impact of battery technology on raw material characteristics is better perceived. This supports the technical design of raw material processing routes as well as awareness for battery-specific requirements. Simultaneously, raw material value chain dynamics are disclosed, facilitating categorization and allocation of indicators and benchmarking factors. Such factors can be used for technology-specific criticality assessments or sustainability analysis of battery raw materials. In the sense of the above-mentioned issue of data availability, the presented approach may serve as a standardized basis to improve data collection. Improved data collection in combination with the proposed blueprint for a value chain also improves the implementation of raw materials among life cycle assessments. The holistic value chain set-up with overarching raw-material definitions and clear boundaries between the stages also facilitates data attribution. This is useful for setting up indicators among sustainability assessments. The approach provides the opportunity to be extended to other raw-material sensitive technologies or products. This also sets the basis to further deep-dive into different (battery) raw materials. Especially life cycle assessments and cost assessments constitute opportunities for application. Furthermore, in the field of the EU Conflict Minerals Regulation the presented approach can be used to set up consistent evaluation schemes and clearly differentiate value chain ranges to be evaluated. Finally, better understanding of battery raw material value chains leads to optimizing and improving these for future needs.

The study still remains and intends to be based upon a scientific approach. Thus, practical applicability is only possible to a certain extent. This represents a dilemma for the underlying topic of lithium-ion battery value chains, as it is inherently characterized by a practical nature. Especially within the field of mining and processing, professional views about technical definitions and classifications are highly influenced by experience and empirical findings. Thus, this might also bring forward discussions about the introduced concept and underlying specifications.

5. Conclusion

With an increasing demand for battery raw materials, impacts on associated commodity markets and underlying value chains are expected. Especially for upstream segments of such value chains, overlapping and interacting stages are inherent. These raw material related value chain stages represent one of the most influential economic factors for lithium-ion batteries. The present work aims to define universally applicable value chain stages for lithium-ion batteries from the mineral deposit to the production of battery cell components. Showing practical applicability of the concept for the battery raw materials lithium, nickel and natural graphite represents an accompanying objective. A two-step methodological approach is inherent to both research targets. Seven general issues for value chain analysis are identified, which are then assigned either to definition (three issues) or to application (four issues) of the concept. The results illustrate a systematic value chain classification from the raw material viewpoint with a technology-specific focus on lithium-ion batteries. The *Raw Material Stage* is associated with typical exploration, mining and beneficiation processes. Subsequently, the concentrate material is upgraded and refined to a market-ready, yet not product-ready level as part of the *Intermediate Material Stage*. The following *Product Material Stage* implements all final, product-specific modifications. Finally, the *Tier-n-Stage* incorporates the product material in the targeted product.

Although no conception approaches for a raw material centered vertical value chain could be identified, reversing and segmenting of a methodology descending from economic management concepts proved to be expedient. With this, a thematically similar methodology has been successfully improved and adapted to fit the discussed topic. Benchmarking of the newly defined value chain stages and steps shows comparable results with publications in the field of battery raw materials. The definition of appropriate terms and stages within the complex topic of mineral economics and lithium-ion technology is subject to certain limitations. Nevertheless, it provides a sufficient interdisciplinary answer serving the holistic perspective. The focus was set on equal consideration of non-metallic and metallic raw material terminology, although non-metallic battery raw materials are still underrepresented. Similarly, addressing fluid raw material deposits with the definition of mining is justified with one of the main source for lithium being brine deposits. In this context, practical standards for appropriate resource reporting of such deposits need to be set up.

The presented approach facilitates data acquisition along the value chain of battery raw materials by providing a suitable framework. When it comes to in-depth considerations of battery raw materials, it can serve as a basis to analyze suitable deposits, products or production routes for example. In addition, a first step towards raw-material oriented life-cycle-assessments is delivered. Within the same context, criticality assessments and sustainability evaluations of battery raw materials can be facilitated. Apart from lithium-ion technology, the described systematic value chain approach can be transferred to other emerging technologies that are outstandingly exposed to raw materials. This may cover but is not limited to other forms of energy storage technologies, 3D printing or mobile consumer-applications.

To conclude, we want to scrutinize the narrow perspective when it comes to the perceived impact of mining and raw materials. Especially concerning lithium-ion technology for automotive applications, the role of metallic and non-metallic raw materials plays a key role for future success and value chains of both branches will intersect. However, both sectors are still considered separately in either perspectives. Thus, an interdisciplinary and joint value chain approach as presented is inevitable.

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Additional materials

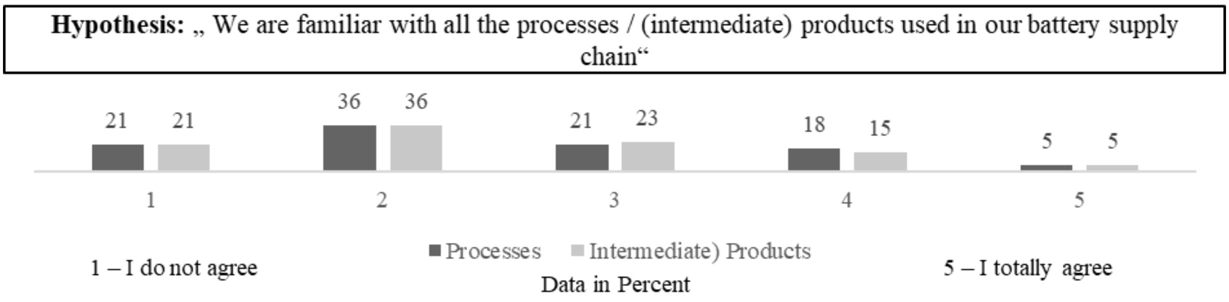

Figure 9: Hypothesis and responses of the PEM related to products along the battery supply chain (translated from German)

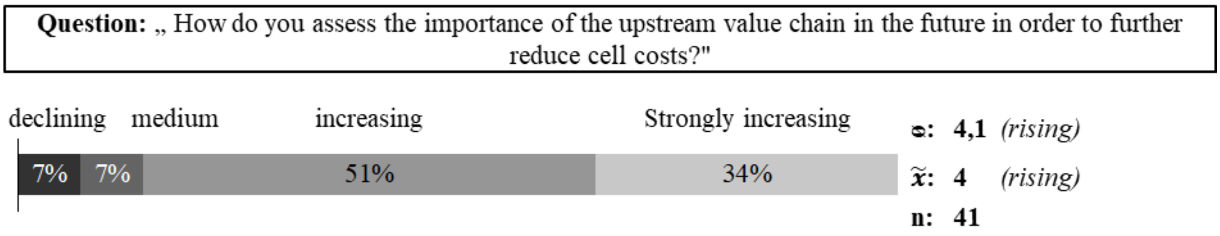

Figure 10: Question and responses of the PEM survey related to the economic importance of the upstream value chain (translated from German)