Evaluation of the Recyclability of Traction Batteries Using the Concept of Information Theory Entropy

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Abstract

As traction battery technologies and electro mobility as a whole continue to grow in importance, the recyclability of batteries has increasingly gained attention in politics, industry and science. The aim of this paper is to broaden the understanding about the recycling of traction batteries by applying the concept of information theory entropy. To this end, information theory-based entropy indicators are used to determine the material mixing complexity of current and future battery chemistries used in electric vehicles. Through the integration of different economic metrics and with the help of additional related information on industrial, political and social influencing factors the recyclability of traction batteries is evaluated and the development of future battery recycling systems and policies is discussed. The results show that the proposed methodology is suitable for comparing different product technologies and that significant differences exist regarding the determining factors for the recyclability of different battery technologies.

1 Introduction

The electrification of transportation is increasingly seen as a solution towards more sustainable mobility. While traction batteries play a fundamental role within the field of electro mobility, their manufacturing and the production of the materials required pose various economic challenges [1, 2]. As of now, traction batteries are made of materials like Lithium, Cobalt and Nickel, which are associated with relatively high material costs and material criticality due to economic importance and geographic concentration [3]. Thus, the secondary raw material streams from the recycling of electric vehicle (EV) batteries may become an important source of materials for new traction batteries. If consistently implemented and executed, recycling might contribute to reducing the demand for primary raw materials [4].

The aim of this paper is to broaden the understanding about traction battery recycling, to discuss a method for determining the recyclability and to identify potential influencing factors in the development of future battery recycling systems and policies at an early development stage. The presented approach builds on existing research by Dahmus and Gutowksi [5] regarding the recyclability of products and applies their proposed methodology for traction batteries. A structured framework to gain relevant information for the recycling of traction batteries is introduced and the recyclability of different battery cell chemistries is compared systematically.

2 Battery Recycling

The transformation of the mobility sector towards electric drivetrains powered by batteries has started only recently within the last decade [6]. Therefore, a significant stream of spent battery packs is estimated to become available within the next ten years. As of today, most Li-Ion batteries are used for consumer electronics products with significantly smaller battery sizes than EV batteries. Recycling technology and capacity exists for batteries of other applications, but is relatively new for EV batteries. Currently, there are only few dedicated industrial recycling facilities. However, more capacities are planned due to the predicted increasing demand over the coming years.

Battery recycling generally uses mechanical, pyrometallurgical and hydrometallurgical processes, usually used in combination [7]. As a first step, there are pre-treatments of battery packs and modules, such as deep discharge and disassembly of the peripheral parts like the housing, cables and power electronics. This step is followed by mechanical processes (shredding, sorting, drying, sieving, etc.) with subsequent pyrometallurgical and hydrometallurgical treatments. Melting processes have already been successfully implemented on an industrial scale, as they are the most economical solution for the currently small stream of spent batteries. They are also the most robust processes for the heterogeneous input waste streams. There is a variety of different technologies, sizes and geometries for current and future EV batteries [7]. This growing product diversity, complexity and resulting material dilution within batteries is threatening to become a major obstacle in successful industrial battery recycling. These factors are equally relevant for the upstream disassembly of battery packs and the following treatment of the active material of battery cells.

To ease disassembly and recycling of complex products, well established methodologies like Design for Recycling (DfR) and especially Design for Disassembly (DfD) strategies and guidelines [8] are available, e.g. by standardizing module geometries or joining technologies and locations. This way the valuable battery module and pack housing materials like steel or Aluminum can be recovered and the battery cells separated. However, a viable option to improve the battery cell

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material recycling processes could be to specialize the processes on those material compositions which have the best recyclability. To determine and compare the recyclability of products, so called entropy indicators have been applied successfully, e.g. in the case of electronics [9] or photovoltaic modules [10]. This paper provides a case study on the recyclability of EV battery systems with the help of material complexity indicators based on the Shannon entropy from information theory [5]. Consequently, the underlying methodology is presented in the following chapter.

3 Methodology

With regards to the aim of this paper and under consideration of existing approaches this paper provides a methodology for determining the recyclability of current and future battery technologies (see Figure 1). It builds on prior research by Rechberger and Brunner [11] as well as Gutowski and Dahmus [5, 12], who use information theory entropy to describe the recyclability of products. It consists of six steps with a cascading character, as every information output is used in the subsequent step. The 1st step of the methodology serves the identification of relevant technologies based on the evaluation of technology roadmaps, in order to determine the technological scope of the analysis. Based on the technological scope, a material analysis is conducted in the 2nd step. Material inventories and stoichiometric calculation of mass fractions are used to provide product compositions and material concentrations. This information is included in the 3rd step together with material prices and the Sherwood methodology to identify those materials which are targeted in recycling. Thereafter, the Shannon entropy is calculated together with the sum of single recycled material values. The 5th step integrates further economic metrics to derive a comprehensive economic perspective. With the help of additional related information on industrial, political and social influencing factors, the 6th and last step serves the overall analysis and discussion of strategies on how to increase the recyclability of the relevant product. In the following, the six steps of the methodology are presented in detail.

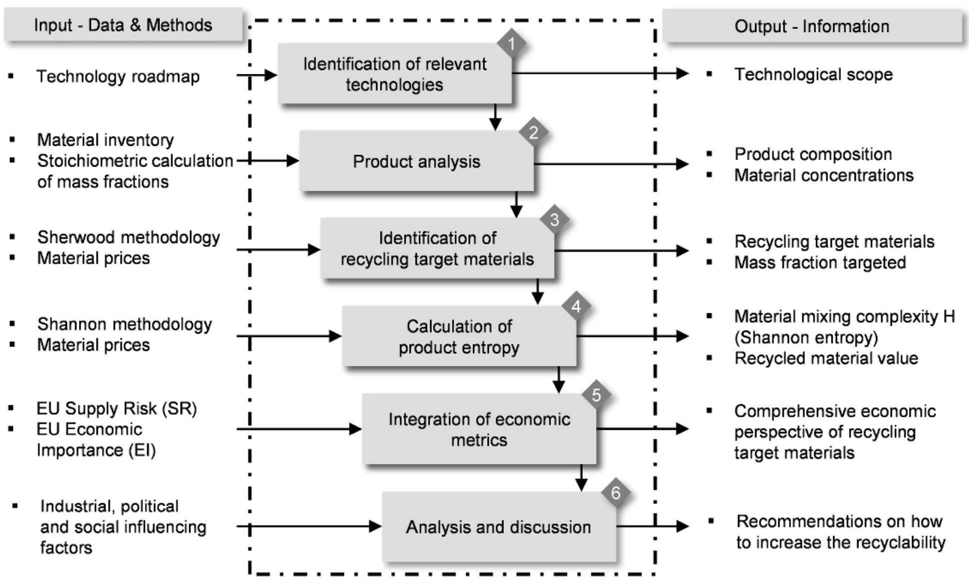

Figure 1. Methodology for the analysis of the recyclability of complex products

Step 1: Identification of Relevant Technologies

The 1st step is a technology screening and identifies the relevant technologies from a selection of market studies, technology roadmaps and expert knowledge. Market studies and experts provide valuable information about the technologies that are relevant to the industry and for recycling. The technology roadmaps provide information about the development of the technology within the next years. Future developments should be considered in the analysis when the product life cycle is expected to last relatively long, since it results in a temporal shift for the waste streams to enter recycling. This is especially the case for the battery cell technology development. The output of this step is the technological scope and should contain all relevant product technology variants.

Step 2: Product Analysis

The 2nd step is the analysis of the components and mass fractions of the identified technologies. Preferably, real inventory data should be used for the material analysis in order to get realistic results. Experience shows that models tend to provide an optimized material inventory that includes less peripheral parts than real recycling studies, especially for battery technology. This is mainly due to over-engineering of safety housing parts for increased product safety. However, in some cases models need to be used, because of lacking published data or data for future technologies that does not exist at the time of performing the study. Based on mass distributions of components and their material compositions, mass fractions of each material can be calculated on component and product level. Stoichiometric calculations are an important tool for this.

Step 3: Identification of Recycling Target Materials

The 3rd step uses the results of the second step, detailed product compositions and exact material concentrations, as well as corresponding material prices and the Sherwood methodology [13] in order to identify materials that should be targeted during recycling, as proposed by Dahmus and Gutowksi [5]. Sherwood [13] indicated that the selling prices of virgin materials vary approximately proportionally with their degree of concentration in the matrix from which they are extracted. Figure 2 on the left shows the relationship between the concentration of a target material in the extraction matrix and the market value of a target material for metals and medicine products. The underlying idea using the Sherwood plot is that materials, which lie above the Sherwood line, are potential candidates for recycling; materials that lie beneath the Sherwood line are considered not valuable enough or too diluted for extraction and recovery. Allen and Bemanesh [14] transferred this approach to examine the economic potential of industrial waste streams and Johnson et al. [9] proved that the Sherwood plot is useful for predicting which materials to target when electronics like mobile phones and personal computers get recycled. This can be seen in Figure 3 on the right, as historically targeted materials lie above the Sherwood line.

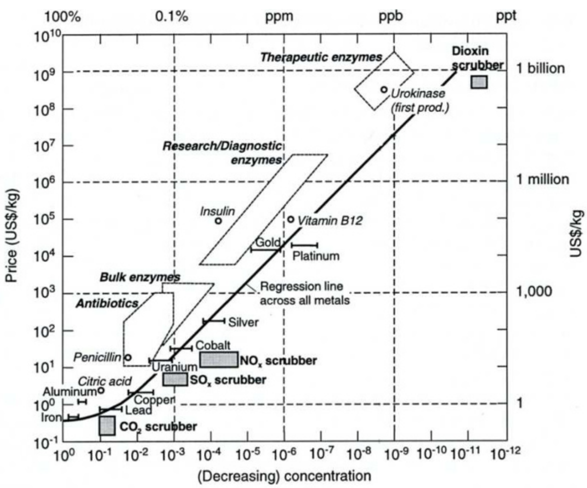

Figure 2. Sherwood plot showing the relationship between the concentration of a target material in a feed stream and the market value of the target material [15]

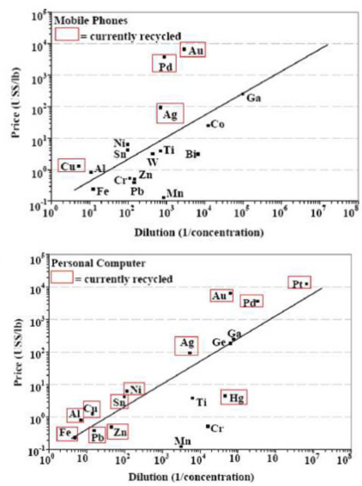

Figure 3. Use of Sherwood plots in the context of electronics recycling [9]

Step 4: Calculation of Product Information Theory Entropy

In the 4th step, the previous results – the information about which materials to target – as well as the material prices are used within Shannon's noiseless coding theorem, which is a method originally used in information theory and is based on L. Boltzmann's statistical description of entropy. In information theory, it is used to measure the loss or gain of information about a system, whereas in statistics it is used to measure the variance of a probability distribution. In the context of material recycling, the Shannon entropy is used as a proxy for material mixing complexity in order to assess the separation and recovery efforts of pure substances from the product. It was first adapted to material recycling by Dahmus and Gutowski [12] and later on expanded by Mohamed Sultan, Lou and Mativenga [16]. A related indicator, the Rényi entropy, was used by Fthenakis and Anctil [10] in a study on photovoltaic panels. Here, the Shannon entropy H is a function of the number of component materials in a mixture M and the mass fraction of each material of the total composition c_i. Therefore, H can be calculated using Formula 1:

$$H = -\sum_{i=1}^{M} c_i \log_2 c_i \text{ [bits]} \quad (1)$$

Gutowski and Dahmus [12] plotted the relationship between the sum of the recycled material's value and the material mixing complexity H and introduced an 'apparent recycling boundary' as shown in Figure 4 [5].

The output of the 4th step can be seen in Figure 4. The expansion by Mohamed Sultan and colleagues [16] was not deemed applicable for traction battery technologies. The authors integrate the recycling Technology Readiness Level (TRL) and Material Security Index (MSI) into their methodology. For some cases the expansion will not bring any additional information, as the TRL of relevant recycling technologies is similar and because the MSI aggregates a great number of Key Performance Indicators (KPI) from different fields into a single numerical value and can therefore produce misleading results. This is the case for the battery technology analysis. Nevertheless, further factors were included into the analysis, as material mixing complexity provides a good indication of product recyclability, but is not the only determining factor. There are manifold external influences onto the recyclability. These influencing factors include the availability of recycling technology, availability of recycling waste streams, efficiency of recycling technology, demand and supply for materials, political situation, product material criticality, etc. The majority of those factors can be categorized as economic influences.

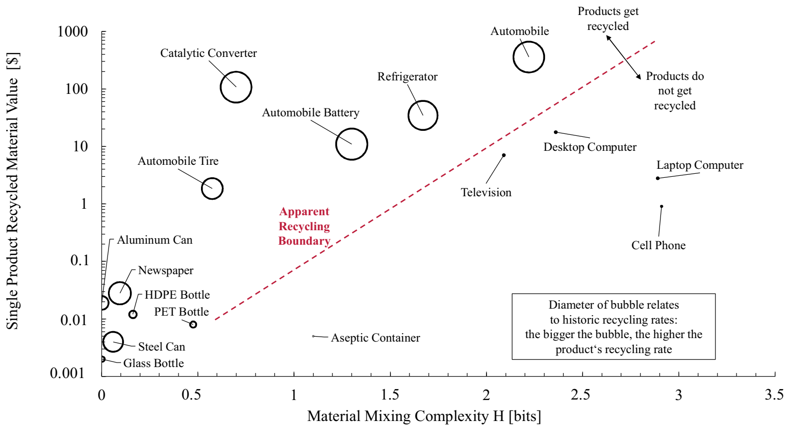

Figure 4. Relationship between recycled material value, material mixing complexity, recycling rate (data from 2007) and apparent recycling boundary [12]

Step 5: Integration of Economic Metrics

The 5th step includes economic metrics into the analysis. The economic criticality of a material can be expressed through different indicators. The EU uses two metrics to assess the criticality of a material, the Economic Importance (EI) and the Supply Risk (SR) [17]. The EI is a quantifiable metric of the relevance of a specified material for the European industry. It takes into account the share of consumption of a material in end use applications and the value added of the corresponding manufacturing sectors. It is adjusted by the substitution indicator that addresses the interchangeability of materials with similar costs and technical properties. The indicator is scaled to a range from 0 to 10, with a higher value indicating a higher economic importance for the European economy [17]. The SR on the other hand addresses the risk of a material supply disruption in the EU and consists of three factors. It considers the political stability and level of concentration of the producing respectively material processing countries. Furthermore, it addresses the substitutability of a material for the economy based on a weighted average calculation over all industries. Additionally it includes the extent to which the European demand for a material is supplied from recycling [17]. These metrics are adopted in this study, since on the one hand they provide insights into the manufacturing sector, which is assumed to grow over the next years for battery manufacturing. One the other hand, the SR incorporates the material scarcity, political stability of producing countries, existing material recycling capabilities and how well these materials can be substituted by similar materials. These factors are highly relevant for the materials for battery cells, specifically Cobalt, Nickel and Lithium [18].

Step 6: Analysis and Discussion

Finally, the 6th step analyses and discusses the results of the previous steps based on a comprehensive perspective. Additional information such as market trends, technology development, material price predictions, expected regulations or possible business models is put into the context of the analysis. The influence of these factors onto product recyclability is discussed and summarized. The results of the analysis are projected onto guidelines or strategies to increase the recyclability of the product technology. Restricting as well as supporting factors are identified from an economic and political perspective.

4 Case study: Batteries for Electric Vehicles

4.1 Step 1: Identification of Relevant Technologies

Traction batteries used currently within electric vehicles are based on Lithium-Ion (Li-Ion) technology. There are different chemistries used for electric and plug-in hybrid electric vehicles (PHEV) in different countries and for different EV brands. Generally, these chemistries are used as cathode material coated onto an Aluminum current collector combined with a Graphite coated Copper anode. The main technologies currently used in EV are NMC, NCA, LFP and LMO respectively LMO/NMC. NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) is used mostly by Tesla. NCA has the advantage of providing a high capacity and voltage, but is more vulnerable to safety problems and is expensive [19]. LFP ($LiFePO_4$) based cell chemistries are mostly used by Chinese EV manufacturers [20]. They provide a high cycle life but low energy densities. Very high energy densities within Li-Ion batteries are currently achieved by NMC (NMC111 – $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$) based cell chemistries, used in most EV [6]. However, NMC cells are relatively expensive due to their high shares of Nickel and Cobalt [2]. The NCM technology is evolving at a fast pace. For this study, a material inventory was considered based on a conventional EV battery provided by Diekmann et al. [3]. Cerdas et al. [21] provide a more recent material inventory for an energy optimized NMC cell, which is characterized by a higher specific energy or energy density. In order to identify both inventories in the figures, the inventory provided by Cerdas et al. is named high energy (HE)-NMC. Research for this chemistry aims at increasing the share of Nickel in the cathode towards currently already used NMC622 ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$) and eventually NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) and to add silicon to the anode of the battery [22]. In the past, LMO ($LiMn_2O_4$) has been used for EV. Due to the better performance of the state-of-the art technologies, it is now less common to be found within EV batteries [6].

The battery industry is characterized by fast technological developments. New chemistries are developed within short time frames with expected market introductions in the coming years until 2030. One example for next generation batteries is the Lithium Sulphur (Li-S – LiS_8) battery, which may see use within EV once the low cycle life can be improved and the challenge of the high volume can be overcome [21]. Additionally, post-Lithium batteries, such as Sodium Ion (Na-Ion – $Na_{1.1}Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05}O_2$) batteries, may see their market introduction in the next decade [23]. Next to batteries for EV, there is a variety of chemistries used for other applications, e.g. stationary applications. These are not taken into consideration for this study. Table 1 provides an overview of the technological scope of this study, respectively the considered battery types and their key attributes.

Table 1. Technological scope of the study – Considered battery types

Battery Type	Mass [kg]	Specific energy [Wh/kg]	Format	Data Source Type	Source
NMC	350	105	Pouch	Real battery	[3]
HE*-NMC	340	150	Pouch	Real battery	[21]
LMO/Gr	63	130	PHEV (prismatic)	Real battery	[19]
LMO/Ti	106	130	PHEV (prismatic)	Real battery	[19]
NCA/Gr	76	110	PHEV (prismatic)	Real battery	[19]
LFP/Gr	82	90	PHEV (prismatic)	Real battery	[19]
Na-Ion	343	102	18650 (cylindrical)	Battery model	[24]
Li-S	340	150	Pouch	Battery model	[21]

*energy optimized NMC cell (HE: **H**igh **E**nergy)

4.2 Step 2: Product Analysis

Spent batteries usually enter the recycling waste stream as battery packs. Additionally to the cells, these battery packs consist of a battery management system (BMS), a cooling system, power electronics and sensors as well as structural elements for mechanic stability and safety [25]. These components are part of the module and pack periphery that consists mainly of steel, Aluminum and plastics, which in total can make up to 25-45% of the weight of NMC battery packs [3].

Cells consist of the components anode, cathode, separator, electrolyte and cell housing. Each cell technology uses different materials for its components. The anode for most cells consists of a Copper current collector foil, which is coated with slurry consisting of Graphite, binder, Carbon Black and a solvent that fully evaporates during the production process. Technologies with different anodes are Li-S with a Lithium metal anode and LMO/Ti with spinel structured Li-Titanate anode. The key differences between the cells are on the cathode side. All cells use an Aluminum current collector foil, which is coated by different cathode slurries. Similar to the anode, the cathode slurry consists of the active material, binder, Carbon Black and solvent. For each cell chemistry, the material composition of the cathode material is calculated using stoichiometric calculations. The separators used in battery cells are based on either polymer or ceramic. There is a variety of electrolytes available and used within cells. However, they cannot be recovered from recycling with

the currently available recycling technologies. The cell housing typically consists of Aluminum or steel for hard case cells and a composite Aluminum-polymer foil for pouch cells. A typical distribution of materials is shown in Figure 5 for a NMC battery system.
Based on the results for the material analysis for each cell, the material inventories are set up. They contain the cell materials and their concentration within the cell. The results are shown in the Sherwood plots in Figure 6, with the dilution as the inverse of the concentration computed on the x-axis. The most common materials within most cells are Copper, Aluminum and Graphite. According to the cell chemistry, other metals such as Nickel, Cobalt, Manganese and Titanium can be identified. Generally, the Lithium content that can be found within cells is relatively low compared to other elements.

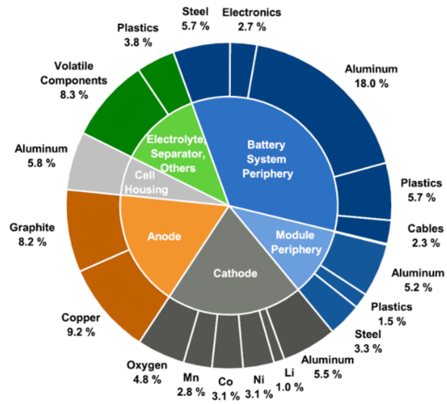

Figure 5. Generic composition of a NMC EV battery system [3]

4.3 Step 3: Identification of Recycling Target Materials

As the level of details for the provided material inventory is different for each study, it is necessary to first define a consistent material counting scheme. This is derived from the Sherwood plots in Figure 6. Materials above or relatively close to the Sherwood line are considered sufficiently rewarding for targeting during recycling. However, other arguments are also considered for the selection of materials, e.g. the effort to recover the materials from the recycling stream. The red underlines in Figure 6 mark the materials that are targeted during recycling. These materials and their concentration are considered in the calculation of the material mixing complexity. The Sherwood plots in Figure 6 show that Lithium, due to its low concentration, may not be within the material with the highest recycling priority from a cost and dilution perspective. Aluminum, Cobalt, Nickel, Manganese and Copper generally have concentrations high enough to be considered as target materials for recycling. Sodium and Sulphur from the new battery generations have a relatively low market value and therefore are not considered for recycling. Since the electrolyte cannot be recovered with a sufficient quality in current recycling processes [3], the values have been neglected. The ratio between prices of virgin and recycled materials was established based on average price differences between new and scrap materials by Anctil and Fthenakis [10], who found that on average a recycled material is worth 60% of a virgin material. This assumption has been adopted for the present case study. The underlying data for the analysis is shown in Table 2.

Table 2. Material data and sources

Material	**Price** (virgin) [€/kg]	**Price** (recycled) [€/kg]	**Economic Importance** (EI)	**Supply Risk** (SR)	**Source** (Price)	**Source** (EI & SR)
Al	3.51	2.11	6.5	0.5	[26]	[27]
Co	33.61	20.16	5.7	1.6	[26]	[28]
Cu	7.87	4.72	4.7	0.2	[26]	[27]
Fe	0.61	0.37	6.2	0.7	[26]	[27]
C	1.29	0.77	2.9	2.9	[29]	[28]
Li	5.56	3.34	2.4	1	[30]	[27]
Mg	4.26	2.55	3.7	0.7	[26]	[27]
Mn	39.42	23.65	6.1	0.9	[26]	[27]
Ni	26.15	15.69	4.8	0.3	[26]	[27]
Ti	2.82	1.69	4.3	0.3	[31]	[27]
Other	*	*	*	*	-	-

* assumed zero

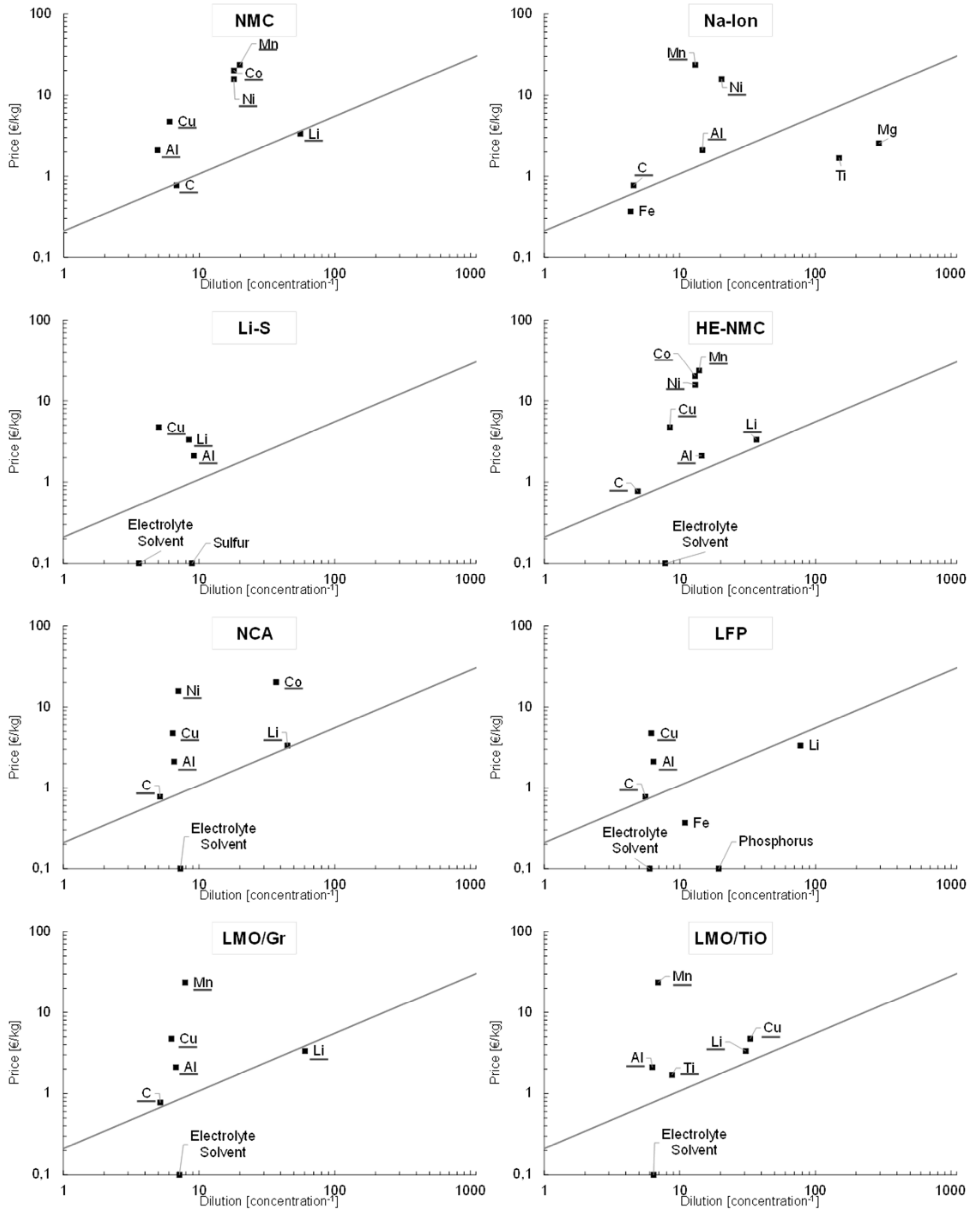

Figure 6. Sherwood plots for battery cells for NMC, Na-Ion, Li S, HE-NMC, NCA, LFP, LMO/Gr and LMO/Ti

4.4 Step 4: Calculation of Information Theory Entropy

The results from the Sherwood plots are used to determine the materials included within the Shannon entropy calculation. Not all materials are considered for the Shannon entropy. A reason is the lack of information about the materials or material compositions of some components that are missing in the inventory data provided in the studies. As shown in Table 3, the range of considered mass fraction lies between 70 % for NMC and 43 % for Li-S.

The results of the Shannon entropy method are displayed in Figure 7. In order to establish comparability between the battery technologies, the results for the material value are normalized to the battery capacity (per kWh). As the present paper does not compare different products, but instead different technologies for the same product, this approach is applied in accordance to the normalization approach by Anctil and Fthenakis [10].

The Shannon entropy ranges from the relatively simple Li-S battery technology (H = 1.18) to the complex technology of NMC batteries (H = 2.09). Both considered NMC battery packs have a relatively high Shannon entropy that relates to a high product complexity. The Shannon entropy for most traction batteries lies within a relatively narrow range of 1.5 to 2.0.

The results for the sum of single material values indicate a significant difference between the battery technologies. The material value per kWh considered for recycling ranges between 6.78 € per kWh battery capacity for Li-S to 31.37 € per kWh battery capacity for the NCA/Gr technology.

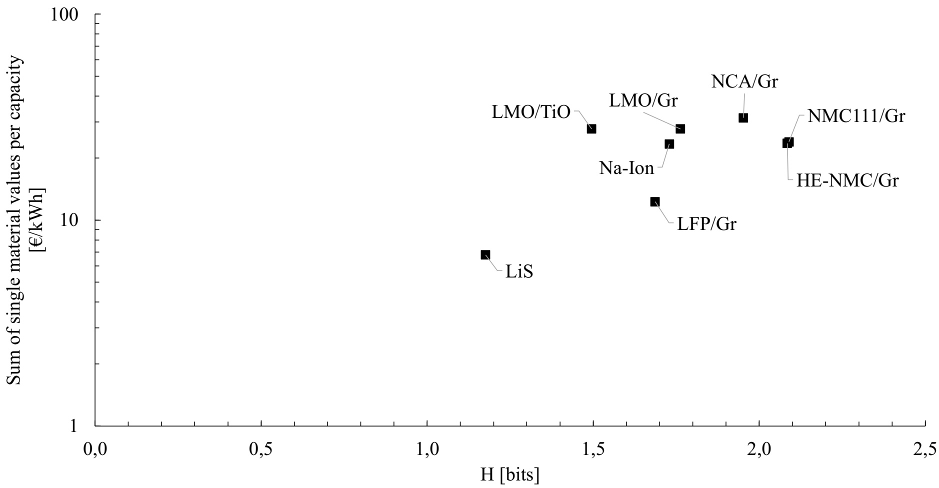

Figure 7. Shannon entropy for battery chemistries; sum of single material values are normalized to 1 kWh.

Table 3. Selected results of case study

Battery Type	Mass fraction considered in Shannon entropy	Shannon entropy (H) [bits]	Sum of material value [€/kWh]	Economic Importance (EI) [EI/kWh]	Supply Risk (SR) [SR/kWh]
NMC	70 %	2.09	23.96	18.14	3.83
HE-NMC	65 %	2.09	23.56	12.38	3.87
LMO/Gr	64 %	1.76	27.69	20.02	5.17
LMO/Ti	48 %	1.50	27.69	17.35	1.86
NCA/Gr	69 %	1.95	31.37	24.57	6.01
LFP/Gr	60 %	1.69	12.28	27.15	6.64
Na-Ion	64 %	1.73	23.40	25.48	7.20
Li-S	43 %	1.18	6.78	8.36	0.92

4.5 Step 5: Integration of Economic Metrics

Economic metrics considered in this study include the sum of material values embedded in the cell, the Economic Importance score (EI) and the Supply Risk (SR) of the EU. The results for EI and SR for each battery technology are displayed in Table 3. They have been normalized to the battery capacity in order to enable comparability between the battery technologies, since technologies with a lower energy density require more material or cells to reach the energy requirements for an EV battery pack. From a recycling perspective, high values for the embedded material values, EI and SR as well as low values for the Shannon entropy positively influence the recyclability.

The main contributor on the SR results is the Graphite of the anode. It contributes in-between 60% to 70% to the SR for all battery cells using graphite. Li-S and LMO/TiO achieve significantly lower SR scores for their material mixes, since they use different anode materials.

Approximately 80% of the sum of material values for recycled material for both NMC cells is contributed by Nickel, Manganese and Cobalt. Considering the drastically rising prices for these materials in recent years, the efficient recycling of these cathode materials will be crucial for the recycling industry. The high specific energy of the NMC technology leads to relatively low EI and SR scores per kWh.

Other current battery technologies, such as LFP and NCA also have relatively high EI and SR of the embedded materials. LFP cells consist of relatively cheap materials that reduce the embedded material value, whereas the high Nickel content in NCA is a main contributor to the high material value.
The material mix of Li-S cells has a relatively low value, with low values for the EI and SR. Therefore, it can be stated, that it is unlikely that they will achieve high recycling rates from a purely economic perspective. Na-Ion cells on the other hand achieve high values for EI and SR, which are mainly caused by the high Manganese content within the cells, which makes up to 50% of the value of recycled materials within the cell.
Finally, it is important to notice that the materials used for the module and cell housing, cables and power electronics also have high material values and EI respectively SR scores that makes them reasonable target materials for recycling. Therefore, an efficient pack and module disassembly is a critical step in battery recycling.

4.6 Step 6: Analysis and Discussion

The results for the selected battery technologies for this case study show a high dilution of embedded materials in different current Li-Ion batteries. Two trends will have a major impact on the dilution. First, current technology development aims at lowering the expensive and critical metals within the battery, such as Co, Mn and Li. This leads to higher dilutions and eventually worse recyclability. Second, the general aim of current development is to lower the inactive materials in order to achieve higher energy densities. One the one hand, this trend results in a positive influence on the recyclability due to the better-balanced material concentration of the battery system. Inactive materials from the housing will have a higher dilution and active materials from the cells a lower dilution. On the other hand, on a cell perspective the material dilution decreases, which makes it more difficult to separate the materials efficiently and has a negative impact on possible recycling rates.
The Sherwood plots in Figure 6 show that most materials used within the cells have a relatively high material value. In recent years, the price for materials for EV batteries has increased dramatically [6]. Higher material values have a positive influence on the recyclability and may have a critical influence on industry and governments to implement efficient recycling structures and to ensure a high return rate of spent batteries. The NMC technologies are the most complex battery technology identified in this study. NMC is expected to increase its market share significantly to up to 68% in 2025 [6]. Together with the presented technology trends, this poses a major challenge for the development of efficient recycling processes and the recyclability of battery cells.
In order to increase the recyclability of Li-Ion battery cells, two strategies can be identified through the application of the methodology. The economic value (sum of single material values) per kWh can be increased and the material mixing complexity within the cells can be reduced. Both strategies imply incorporating more expensive and scarce materials like Li, Co, Ni and Mn. This stands in contrast with the explained current trends in battery development and industry interests. However, as the analysis of the Economic Importance and the Supply Risk indicates, there is a strategic interest in securing the embedded materials for future production purposes. Hence, governmental regulations that aim to increase the recycling quotes and to strengthen a circular economy are likely to be implemented in the coming years. Furthermore, new business models for EV batteries, e.g. product service systems where the battery manufacturer remains the owner of the battery, can provide incentives to design better recyclable batteries as the companies will be able to recover more materials in a better quality.

5 Conclusion

This paper presents a six-step methodology to determine the recyclability of products by contrasting material mixing complexity and economic incentives for recycling. The methodology is applied in a case study on current and future traction battery cell technologies and establishes comparability between the technologies by normalizing the results to the battery capacity (per kWh). Generally, battery cells are relatively complex products with a high material mixing complexity. Predictions about a technology's recycling rate were not made, because most batteries are situated on the 'apparent recycling boundary' defined by Dahmus and Gutowski [5]. Nevertheless, there are significant differences regarding the determining factors for the recyclability of different battery technologies. Li-S was identified as the technology with the lowest material mixing complexity, but also with the lowest sum of recycled material value as well as the lowest scores for EU Economic Importance and Supply Risk. LMO-based technologies have moderate material mixing complexity and high scores in the economic metrics, indicating that LMO-based technologies possess a comparatively good recyclability. The same applies to Na-Ion battery cells. Whereas LMO is perceived as a declining technology, the latter is a technology with potential application in the future. NMC is the currently preferred technology with a high research intensity. The results from this study indicate its recyclability is worse than other technologies. The trend towards higher material dilution of expensive materials will further decrease the recyclability. It requires further research to fully analyse this effect.
The proposed methodology is suitable for comparing different product technologies as done in the case study. Due to the electrochemical processes throughout the battery life, the embedded materials are hard to separate at the end of life. Hence, cell disassembly is not viable in most of the cases. The presented method provides broader information into recyclability, which can be used in DfD and DfR methods in order to improve future recycling efforts. Further extension

potential can be identified to increase the informative value and decrease the uncertainty, such as incorporating environmental metrics or the integration of a scenario based analysis with different material prices as underlying variables.

6 Zusammenfassung

Während die Bedeutung von Antriebsbatterien und Elektromobilität insgesamt an Bedeutung gewinnen, hat die Frage nach der Recyclingfähigkeit der Batterien das Interesse von Politik, Industrie und Wissenschaft erregt. Ziel dieses Beitrags ist es, das Verständnis des Recyclings von Antriebsbatterien durch Anwendung des informationstheoretischen Konzepts der Entropie zu erweitern. Zu diesem Ziel werden informationstheoretische Entropieindikatoren verwendet, um die Komplexität des Materialmixes heutige und zukünftig in Elektrofahrzeugen verwendeter Batteriechemie zu bestimmen. Durch die Integration verschiedener ökonomischer Werte sowie industrieller, politischer und sozialer Einflussfaktoren wird die Recyclingfähigkeit der Antriebsbatterien evaluiert und die Enwticklung zukünftiger Recyclingsysteme für Batterien diskutiert. Die Ergebnisse zeigen, dass die verwendete Methode geeignet ist um verschiedene Produkttechnologien zu vergleichen und dass signifikante Unterschiede in Bezug auf die die Recyclingfähigkeit bestimmenden Faktoren verschiedener Batteriesysteme bestehen.

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