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Exploring recycling options in battery supply chains – a life cycle sustainability assessment

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Abstract

The increasing demand for battery raw materials is driving countries around the world to establish recycling networks to obtain secondary materials for their battery production. However, the establishment of recycling networks is still at an early stage of development and analysis is needed to support decision-makers in the deployment of recycling networks. Therefore, this paper assesses the environmental, economic, and social impacts of three different recycling networks that vary in size and number of recycling sites in Germany. It also evaluates the effect of different battery sizes and chemistries on favorable recycling networks and compares the impacts related to primary and secondary materials. The results indicate that large and centralized recycling facilities are advantageous. They also show that secondary materials offer a great opportunity to reduce environmental, economic, and social impacts.

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Keywords: Life Cycle Sustainability Assessment; Batteries; Primary Materials; Secondary Materials; Supply Chains; Recycling networks

1. Introduction

The emerging production of traction batteries for electric vehicles in Europe leads to an increasing demand for battery raw materials. Since only a small fraction of the raw materials can be mined in Europe, large amounts have to be imported. The global battery supply chains are not only associated with several environmental and social concerns but also induce strong economic dependencies [1]. Moreover, the ever-growing volume of waste batteries must be collected and treated appropriately. This calls for the deployment of an effective recycling system. To establish such recycling systems, car and battery manufacturers pursue various strategies. However, the recycling of waste batteries from electric vehicles is still at an early stage of development so that there are considerable uncertainties regarding the best network design [2]. Consequently, it is necessary to support the decision-makers with assessments of different recycling

strategies. Currently, the focus of these assessments is on the present and potential recycling routes. For example, Cerdas et al. and Thies et al. investigate environmental and economic aspects of the LithoRec recycling process, respectively [3,4]. Furthermore, studies exist that compare the common recycling routes for different battery chemistries regarding these two dimensions [5–8]. Recycling is included as one phase in holistic Life Cycle Assessments (LCA). However, in these studies, recycling is analyzed in an aggregated manner so that no detailed recommendations can be derived for the decision-makers [9–11]. The derivation of recommendations is further hindered by the fact that most studies do not include a detailed consideration of recycling networks and the corresponding transport, as emphasized by Slattery et al. [12]. Only a few authors have assessed possible recycling networks, e.g., in California and China [13–15]. However, a comprehensive sustainability assessment of recycling networks in Europe is still pending. Only some studies exist

that assess particular aspects, such as the economic assessment and optimization of recycling networks in Germany by Hoyer et al. [16]. Furthermore, none of the studies include an assessment of the social dimension, which is crucial for comparing the use of secondary with primary materials in battery production.

Thus, the aim of this article is to explore and analyze different design options for recycling networks within a battery supply chain in terms of their environmental, economic, and social impacts using a Life Cycle Sustainability Assessment (LCSA) approach. To this end, several parameters are examined in detail: the size of recycling facilities, transportation distances, and the impact of different battery chemistries and sizes. These parameters are studied because a large impact is predicted from them.

The remainder of this article is organized as follows. First, the LCSA approach is briefly introduced and the used impact assessment methods are described in Section 2.1. Next, the investigated systems are defined in Section 2.2 and the life cycle inventories are described in section 2.3. In Section 3, the results are presented and discussed. In addition, the impacts for the main secondary materials are compared to the impacts of the respective primary materials. Finally, a conclusion and an outlook for future research are provided in Section 4.

2. Life Cycle Sustainability Assessment

2.1 Method definition

The LCSA approach that is used to assess the recycling networks comprises individual assessment methods for each of the three sustainability dimensions [17,18]. It builds on the ISO 14040/14044 standards, which set the framework mainly for the environmental Life Cycle Assessment (eLCA). However, the social Life Cycle Assessment (sLCA), as well as the environmental Life Cycle Costing (eLCC), use similar structures [19,20].

To assess the environmental impacts of the investigated recycling networks, the ReCiPe v1.13 method is used [21]. With this method, 18 impact categories can be assessed, whereby five are selected for this study. The selected impact categories are: climate change (CC), mineral resource depletion (MD), particulate matter formation (PMF), terrestrial acidification (TA), and terrestrial ecotoxicity (TET).

The social risks are assessed with the respective impact assessment method of the Social Hotspot Database (SHDB), which is used as a database for the sLCA [21]. For the social assessment, the following risk categories are selected: risk of child labor (RoCL), risk of forced labor (RoFL), risk of poverty (RoP), and risk of corruption (RoC).

For the eLCC, four individual impact categories are defined, namely process costs, material costs, transport costs, and revenues. Process costs include all costs associated with an individual process step, such as personnel cost or depreciations for the required machines. The materials used for the recycling process are connected with the material costs,

while the transport between different locations is connected with the transport costs. The revenue depicts the monetary value of materials, which leave the system boundary. The four impact categories are further summed up to get the resulting profit of the investigated recycling networks.

For the calculation of the impacts, the Python-based framework “Brightway2” is used [22].

2.2 System definition

With the defined LCSA approach, 15 cases are assessed. These cases have a common system boundary (Fig. 1).

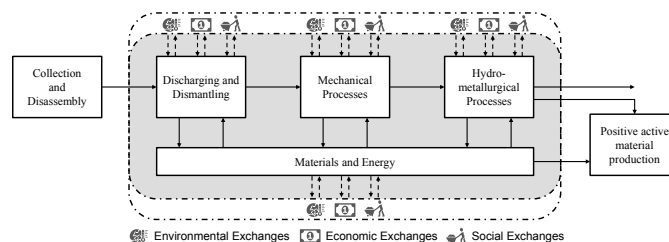


Fig. 1: System boundary of the investigated recycling networks

The investigated systems include the transport of the disassembled batteries of battery electric vehicles (BEV) from the collectors to the respective recyclers. One recycler is assumed to conduct all three depicted recycling processes in the grey area at one location. The recycling process is adopted from the LithoRec process and is divided into three steps [23]. First, the batteries are discharged and the battery packs are disassembled down to the level of the battery modules. The second step involves mechanical processes. In the corresponding processes, the battery modules are crushed and metal, as well as plastic fragments, are separated, resulting in a black mass that is further treated in the hydrometallurgical processes to obtain materials such as cobalt sulfate, nickel sulfate, manganese sulfate, or lithium carbonate. These materials are the main components for the positive active material in which the secondary materials should replace the corresponding primary materials in the future.

Besides the recycling processes, the unit processes for the required materials and energy are integrated into the system boundary. In addition, all these processes within the grey area are connected to environmental, economic, and social data and indicators.

The first goal of the LCSA is to calculate these indicators for the case that 45.000 t of used BEV batteries are recycled in Germany annually. This recycling capacity would be necessary if around 50% of the placed BEV batteries in 2020 are collected in Germany, based on the average battery mass within the current BEV fleet. Thus, the task of the recycling facilities is to recycle this amount of used batteries. Furthermore, three scales from small to large are assumed for the recycling facilities to evaluate the scaling effect on the indicator scores.

Additionally, since the battery chemistries and sizes may affect the assessment results, a distinction between five

different battery configurations is made (Table 1). An NMC622 battery representing the dominant cell chemistry and the average capacity and mass in the current fleet in Germany serves as the reference for the analysis. Further configurations capture currently used batteries on the BEV market. They are used as a comparison to show the effects of different battery sizes and chemistries on the recycling networks.

Table 1: Battery chemistries and sizes

Name	Chemistry	Capacity [kWh]	Mass [kg]
Average NMC622	NMC622	60	428
Large NMC622	NMC622	95	697
Small NMC622	NMC622	42	270
NMC111	NMC111	36	348
NMC811	NMC811	80	520

The second goal of the case study is to compare the impacts for the case that the main primary materials needed to produce one kilogram primary active material NMC622 are replaced by the secondary materials provided by the recycling facilities. For this purpose, the impacts caused by the recycling network under study are allocated among all the materials provided by the recycling processes through a mass allocation. Mass allocation to materials is considered only if the material has a value in the market. If a material is a waste with no value, no impacts are assigned to that material. To analyze the effects of using secondary materials, the proportion of primary materials should be gradually decreased from 100% to 0%.

2.3 Life cycle inventory

Due to the assumption that the three different sizes of the recycling facilities should be considered in the case study, the number of needed locations varies to satisfy this goal. For this article, three different sizes are defined, as shown in Table 2:

Table 2: Sizes of investigated recycling facilities and number of locations

Size	Annual capacity [t/a]	Nr. of locations
Small	2,250	20
Medium	9,000	5
Large	22,500	2

For these sizes, two to twenty recycling facilities are required. The two locations in the first case are based on current recycling facilities, while the second case also includes planned recycling facilities in Germany. Additionally, locations where batteries are produced or will be produced, are selected for possible recycling facilities in the third case. Furthermore, for all production sites of the materials required for the recycling processes, such as sulfuric acid or caustic soda, one location is determined in all three

cases, except for nitrogen production, as the selected supplier has several production sites in Germany.

The transport distances between the recyclers and material suppliers are calculated with the GoogleMaps API. This is also the case for calculating the distances from the collectors to the recyclers. As collectors, all dealers who sell BEVs or provide services for BEVs of a leading car manufacturer are considered for the collection and disassembly. This data is combined with the current distribution of BEVs in Germany to get the average distances from the collectors to the recyclers in the defined cases.

The material composition of the different batteries is calculated with the “Battery Performance and Cost (BatPaC) model” of the Argonne National Laboratory [24]. The data of this calculation are used in the calculation for the recycling processes subsequently.

To compare the substitution of primary materials with secondary materials, it is assumed that the primary materials are extracted and refined in the countries that are the dominating producers of the respective materials, according to the U.S. Geological Survey in 2020 [25].

The data for all required materials and energy processes are extracted from the ecoinvent v3.8. database [26]. Furthermore, all used processes are extended by the economic data and sectors for the economic and social assessment. The economic data used, based on literature as well as on market data. The cost of transportation is calculated based on published data that takes into account key aspects such as average wages, tolls, and distances [27]. For the transportation of hazardous goods, a factor of 1.5 is estimated. The sectoral data are taken from the SHDB [28].

3. Results and discussion

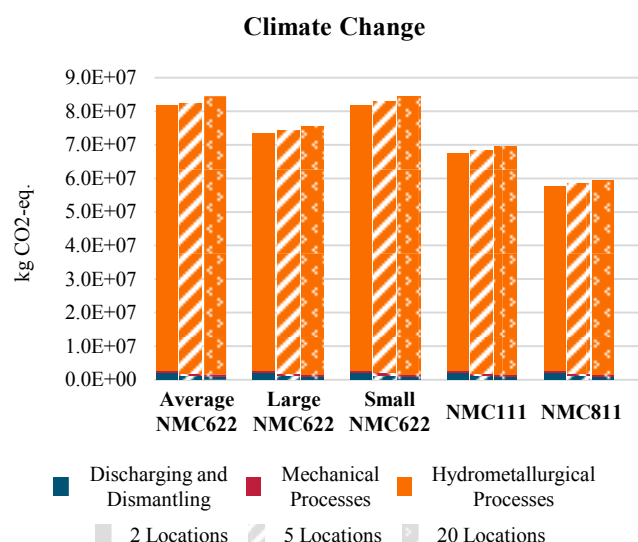
3.1 Environmental impact assessment results

For the environmental assessment of the defined recycling networks, five impact categories are analyzed and compared. The impact scores for the impact category climate change (CC) are depicted in

Fig. 2 as an example.

First of all,

Fig. 2 shows that the hydrometallurgical processes have the highest contribution to the impact scores. For CC, the associated processes are responsible for 95% up to 98% of the emitted CO₂-equivalents. This is due to the electricity required for the hydrometallurgical processes and the production of caustic soda, which are responsible for over 40% of the emissions, respectively. The steps for dismantling and discharging and the mechanical processes have a negligible contribution. Furthermore, the results show that the emissions increase for the cases with more locations. This is due to two effects. First, the average distances between the material suppliers and the recycling facilities increase and are not compensated by the decreasing average distances between the collectors and the recycling facilities. Second, the smaller capacities of the recycling facilities lead to a higher energy



and material demand due to economies of scale. Besides this, Fig. 2 reveals that the recycling of NMC811 leads to fewer emissions compared to the cases with NMC111 and NMC622. This fact is a result of the different battery compositions and the materials required for the hydrometallurgical processes. Fewer materials and energy are required to recycle larger batteries so that the corresponding CO₂-equivalents are lower for the large NMC622 than for the average or small NMC622. For the impact categories mineral resource depletion (MD), terrestrial acidification (TA), and particulate matter formation (PMF), the shares between dismantling and discharging, mechanical processes, and hydrometallurgical processes are similar to the cases depicted in Fig. 2. However, the reasons for the emissions differ. In the case of MD, the production of caustic soda has by far the highest contribution, with shares from 53% to 59%. The depletion of Fe-equivalents associated with caustic soda production is mainly driven by the required materials for the construction of production facilities. Compared to that, the most significant contributor of TA is related to the production of caustic soda, sulfuric acid, and electricity driven by the combustion of fossil fuels for electricity production, which is also the case for the impact category PMF. The results of the impact category terrestrial ecotoxicity show similar effects regarding the locations, recycling facility sizes, and batteries. However, the relative impact of the discharging and dismantling steps is much higher than in the previously mentioned impact categories due to the more considerable influence of transportation processes on the scores of this impact category. The relative contributions vary between 21% and 26% for all cases. Further strong contributions end from producing caustic soda and sulfuric acid driven by electricity production.

Fig. 2: Results for the impact category climate change

3.2 Social impact assessment results

For the social dimension of the LCSA, four impact categories, which are often considered in the context of global

battery supply chains, are analyzed in detail. Fig. 3 depicts the results for the impact category risk of child labor (RoCL).

Similar to the environmental dimension, an increase of the equivalent medium risk hours is visible for the cases with more than two locations. However, the difference is much higher for the social impact scores. This effect is mainly driven by the number of employees necessary for the recycling processes. While the number of employees for the discharging and dismantling steps does not vary if more locations are considered, the operation and monitoring of the machines for the mechanical and hydrometallurgical processes leads to a higher personnel requirement. Thus, the depicted shares for the mechanical and hydrometallurgical processes increase rapidly for all five investigated batteries.

Furthermore, Fig. 3 reveals that the absolute amount of these two processes is similar for all batteries for the respective recycling network. The main difference between the chemistries results through the differences between the medium risk hours for the discharging and dismantling steps. Since fewer battery packs are recycled for the large NMC622 and the NMC811 compared to the average NMC622, fewer employees are needed for these steps resulting in lower equivalent medium risk hours. Thus, the mass of the batteries has an influence on the results of the social impact categories. The effects and impacts scores of the RoCL described are transferable to the other social impact categories examined, namely risk of poverty, corruption, and forced labor. There are only differences in the absolute scores due to the associated risks for the respective impact category.

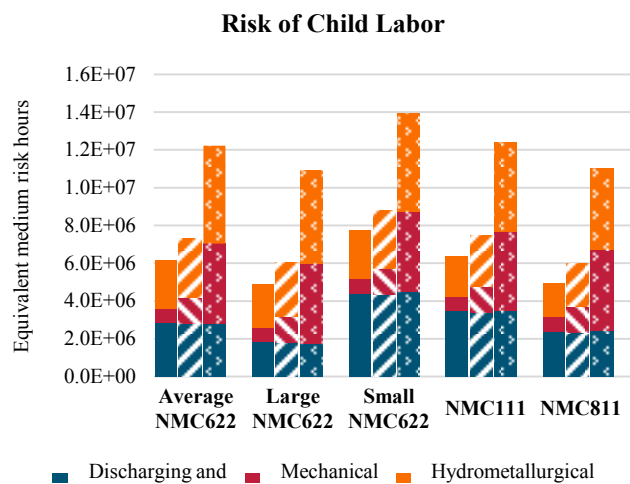


Fig. 3: Results for the impact category risk of child labor

3.3 Economic impact assessment results

For the economic assessment, the results of four impact categories are calculated, which are combined to form the impact category profit. The profit for the different cases is listed in Table 3.

Table 3 shows that the recycling networks are profitable for the cases of two or five locations, while the recycling networks with 20 locations are not profitable in this setting.

Furthermore, the recycling of large NMC622 batteries generates the highest profit, while the recycling of NMC111 leads to the lowest profits. These results are mainly influenced by the economic impact category process costs, in which similar effects as for the social impact categories can be identified. Due to the higher personnel requirements in the case of five and twenty recycling facilities, the personnel costs increase rapidly and, thus, the process costs. The material costs or the revenue do not differ significantly if more locations are considered. However, they differ for the different battery compositions since different amounts of materials for the recycling processes are needed and different amounts of valuable materials are recycled. For example, the recycling process of the NMC811 provides less cobalt sulfate than the NMC622 batteries, leading to lower revenues. Therefore, the revenue is highly affected by the composition of the batteries. The impact category transport costs also has a minor influence on the differences for the profit. However, it should be emphasized that the transport costs associated with the discharging and dismantling step decrease for recycling networks with more locations, while the transport cost increase for the hydrometallurgical processes due to the difference in the average distances between the recycling facilities and the material suppliers.

Table 3: Profit of the investigated recycling networks

Name of the battery pack	Number of locations	Profit [US-Dollar]
Average NMC622	2 Locations	7.17E+07
	5 Locations	5.35E+07
	20 Locations	-2.51E+07
Large NMC622	2 Locations	7.35 E+07
	5 Locations	5.57 E+07
	20 Locations	-2.24 E+07
Small NMC622	2 Locations	5.07 E+07
	5 Locations	3.3 E+07
	20 Locations	-4.78 E+07
NMC111	2 Locations	3.65 E+07
	5 Locations	1.91 E+07
	20 Locations	-5.98 E+07
NMC811	2 Locations	6.4 E+07
	5 Locations	4.72 E+07
	20 Locations	-3.19 E+07

3.4 Comparison of primary and secondary materials

The impact of the stepwise substitution of primary

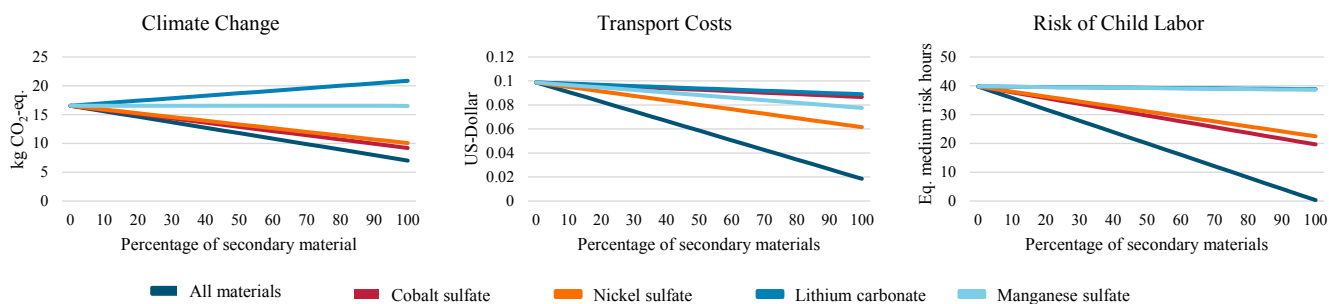


Fig. 4: Reduction potential with the use of secondary materials compared to primary materials

materials by secondary materials is shown in Fig. 4. In the figure, the effects are shown as an example for CC, transport costs, and RoCL for the case of two locations and the average NMC622 battery. Transport costs are chosen because it is assumed that prices for primary and secondary materials are the same. Furthermore, Fig. 4 shows the reduction potentials when all four considered materials are substituted simultaneously or individually.

In the case of CC, it can be seen that the total CO₂-equivalent emissions can be reduced overall. This is mainly a consequence of the reduction potential due to substituting primary cobalt sulfate and nickel sulfate with their secondary counterparts. The use of secondary lithium carbonate has an opposite effect in the cases studied, as shown in Fig. 4, since the indicator score increases due to the use of secondary lithium carbonate. Two reasons can explain this. First, the considered allocation rule has a high influence on the resulting indicator score. Second, the process of producing primary lithium carbonate has a lower influence on CC than nickel sulfate or cobalt sulfate. The substitution of primary manganese sulfate does not show a large difference and thus does not influence the reduction potential.

The transport costs decrease in all cases investigated. This is a consequence of the assumptions made. Since the production of the positive active material and the recycling facilities are located in Germany, the transport distances of the secondary materials are shorter than for the primary materials. However, the reduction in transport costs implied by the substitution of all four materials is mainly influenced by the transport costs for nickel sulfate, which result from the higher mass to be transported, since a higher proportion of nickel sulfate is needed to produce the positive active material.

On the reduction potential of RoCL, the substitution of lithium carbonate and manganese sulfate does not have a significant impact due to the relatively low risk of child labor in the countries producing the raw materials. However, there is a high to very high risk of child labor in the countries producing primary cobalt sulfate and nickel sulfate, so using German-produced secondary materials in place of the primary materials would result in an RoCL that is close to zero.

The impacts described and presented are similar for all 15 cases studied. Furthermore, the CC and RoCL results are transferable to the other environmental and social impact categories studied.

4. Conclusion and outlook

This article presents an LCSA of three different recycling networks that recycle five different batteries. The recycling networks vary in the number of locations and the capacity of each recycling facility. The assessment focuses on the effects of different locations, scales, and battery sizes and chemistries. The results show that a large scale and the case with two locations are beneficial compared to the other cases, especially with respect to the social and economic impact categories. Therefore, it could be recommended to build up large recycling facilities instead of smaller and local recycling facilities.

Moreover, the results show that it is not profitable to operate small-scaled recycling facilities so that it is not recommended to recycle waste batteries with this option. Additionally, a comparison between primary and secondary materials is made in this article. The result is that using secondary materials instead of primary materials in battery production could lead to improvements regarding the impacts. However, the substitution of lithium carbonate does not lead to improvements in the case of environmental impact categories, which could be a consequence of the considered allocation rule. Thus, a sensitivity analysis considering these aspects is required in future research to analyze these effects in more detail to show if the usage of all secondary materials can be promoted in the future.

Furthermore, future studies should expand the system boundaries to include, e.g., the use phase or the battery production as additional sources for material that must be recycled to derive recommendations that consider the whole battery supply chain. Additionally, more parameters should be considered within the study. For example, current and prospective battery mixes or more recycling routes, such as a pyrometallurgical route, and combinations should be considered as different companies use different recycling routes. Furthermore, the scale of the recycling facilities should be varied to give good recommendations for the size at specific locations based on the spatial concentration of waste batteries.

In addition, the results of the social impact categories could lead to the conclusion that automated production would be beneficial, as the workforce required for production is mainly responsible for the high differences between the cases studied. This is questionable since these are well-paid jobs that increase social welfare. Furthermore, the used SHDB refers to risk in a specific sector, which is also connected with other worldwide sectors so that this could lead to overestimating the social risks in the considered countries. Thus, the social assessment can only raise awareness that there might be challenges in these process steps. However, consideration should be given to how the social assessment can be expanded and improved to provide better recommendations in the future.

Considering these aspects in future research will improve the conducted LCSA study and help provide useful

recommendations for designing recycling networks as part of global battery supply chains.

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