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Comparison of lithium-ion battery supply chains – a life cycle sustainability assessment

Jan-Linus Popien[a,c,*], Jana Husmann[b,c], Alexander Barke[a,c], Christian Thies[d], Felipe Cerdas[b,c], Christoph Herrmann[b,c], Thomas S. Spengler[a,c]

[a] Institute of Automotive Management and Industrial Production, Technische Universität Braunschweig, Braunschweig 38106, Germany
[b] Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Braunschweig 38106, Germany
[c] Battery LabFactory Braunschweig (BLB), Technische Universität Braunschweig, Braunschweig 38106, Germany
[d] Hamburg University of Technology, Resilient and Sustainable Operations and Supply Chain Management Group, Hamburg 21073, Germany

* Corresponding author. Tel.: +49-531-391-2215; fax: +49-531-391-2203. *E-mail address:* j.popien@tu-braunschweig.de

Abstract

The increasing number of electric vehicles worldwide leads to various challenges, especially in terms of battery supply chains. New battery production sites, raw material refiners, and extraction sites will be needed to fulfill the future battery demand. Additionally, the planned European Battery Directive requires battery manufacturers to meet defined CO_2-limits and social standards to enter the European market. However, depending on the design of battery supply chains, environmental and socio-economic impacts can vary considerably. Especially the selection of suppliers as well as production locations and processes can have a major influence. Therefore, the aim of this study is to investigate battery supply chain options to highlight the differences and trade-offs related to the three sustainability dimensions. For this purpose, a life cycle sustainability assessment is conducted, considering a baseline scenario depicting the global average production shares, and three additional scenarios to investigate the influence of locations on three processes along the supply chain. The results provide insights into the design of sustainable battery supply chains. It is shown how different locations and battery types affect the indicator scores of the investigated supply chains. Furthermore, the results indicate distinct trade-offs between the three sustainability dimensions and underline the necessity for the subsequent use of multi-criteria decision-making models to derive recommendations for designing sustainable battery supply chains.

Keywords: life cycle sustainability assessment; lithium-ion batteries; battery production; supply chain design

1. Introduction

The global demand for lithium-ion batteries is expected to increase 10- to 20-fold this decade, mainly due to the rapid growth of the electric vehicle market [1]. The growing demand implies that capacities for the extraction and refinement of battery raw materials and the production of battery cells must also be increased. The global distribution of related processing and production facilities directly affects the environmental impacts in the supply chain, which can be explained by the varying production processes, ore grades, and electricity mixes in the respective countries [2–4].

Besides environmental impacts, social considerations are becoming increasingly important for the design of supply chains. For example, the planned EU Battery Directive and the German Supply Chain Act make companies responsible for protecting human rights in their supply chains [5,6]. Therefore, the investigation of social risks, such as poor working conditions, should be included in a comprehensive sustainability assessment.

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Furthermore, companies seek to generate financial profit, so the cost structure of the activities in their supply chain is of great importance. This underlines the need to consider all three sustainability dimensions when evaluating and designing battery supply chains. Only a few studies have done this so far. For example, Thies et al. evaluate three supply chain configurations of a generic battery system [7]. However, their main goal was to develop a new assessment method, and the analysis is limited to one particular battery system.

Therefore, this article aims to assess current battery supply chain options in terms of their environmental, economic, and social impacts based on current production shares. To this end, alternative supply chains for three battery types covering the required steps from raw material extraction to battery cell production are investigated using a life cycle sustainability assessment (LCSA) approach. The investigation seeks to highlight the differences between the supply chain configurations in terms of environmental, economic, and social performance indicators and illustrate the implications of conflicting objectives for the design of sustainable supply chains.

The remainder of this paper is organized as follows: First, the objective and scope of the LCSA study is defined in Chapter 2. Chapter 3 explains the life cycle inventories, while the results are described and discussed in Chapter 4. Finally, a conclusion and outlook are given.

2. Goal and scope definition

The LCSA approach employed in this study consists of three methods for assessing environmental, economic, and social impacts. All three methods are based on the ISO standards 14040/44. Details of the methods can be found in [8–13].

The main goal of this study is to compare alternative supply chains for three types of lithium-ion battery cells regarding their environmental, economic, and social impacts. The assessment is based on country-specific production shares. Furthermore, individual parts of the supply chains, such as the cell production sites or the lithium supply, are investigated in detail to derive deeper insights beyond the analyses of current production shares.

The three investigated batteries are distinguished by their positive active material, namely lithium nickel manganese cobalt oxide (short: NMC811), lithium nickel cobalt aluminum (short: NCA) oxide, and lithium iron phosphate (short: LFP). They were selected based on their current market shares [14]. The cell chemistry not only determines the gravimetric energy density of the battery cells and, consequently, the mass of the battery pack, it also influences the material requirements and energy demand. The functional unit represents the production of battery cells with a total capacity of 10 GWh within one year. This suffices for building 100,000 battery packs with a capacity of 100 kWh each. It is assumed that one battery pack is composed of 400 cells [15,16].

The system boundary depicted in Figure 1 illustrates that we pursue a cradle-to-gate approach that encompasses all activities from raw material extraction and processing to component production and cell production. These activities represent the foreground system, and their inputs and outputs are defined depending on the battery types. Besides the foreground system, an intermediate and background system are defined. The intermediate system consists of ecoinvent processes extended by country-specific economic and social flows to account for the regional differences in the foreground system. The background system consists of the ecoinvent v.3.8 cutoff database and the Social Hotspot Database (SHDB), which contain datasets used as inputs for the activities in the intermediate and foreground system [10,17].

The life cycle sustainability impact assessment builds on the ReCiPe v.1.13 (H) method for the environmental assessment, the SHDB method for the social assessment, and a cost-based method for the economic assessment [10,18]. While these methods comprise a large variety of impact categories, our study focuses on selected impact categories, namely *climate change (CC)*, *metal depletion (MD)*, *terrestrial acidification (TA)*, and *particulate matter formation (POF)* for the environmental assessment, *risk of child labor (RoCL), risk of forced labor (RoFL)*, and *risk of occupational injuries and deaths (RoOI&D)* for the social assessment. Regarding the economic assessment, the total *cost* from a cell producer's perspective is considered. It includes depreciation of machines and buildings as well as personnel, material, transport, and electricity costs.

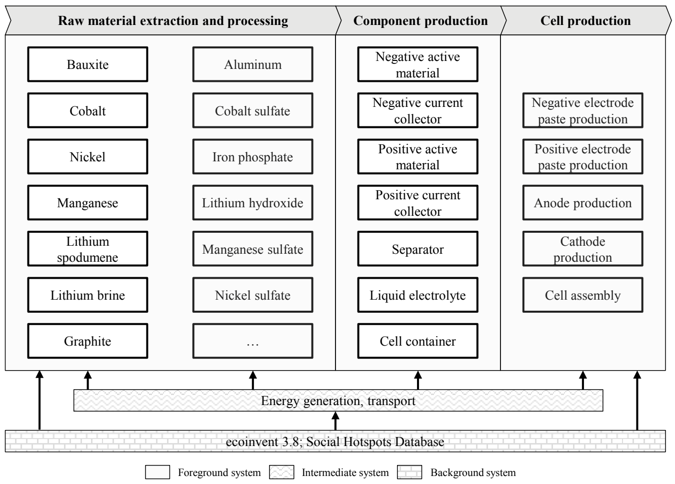

Figure 1: System boundary of the LCSA study

3. Life cycle inventory

Based on the goal and scope definition, the life cycle inventories are created for the three battery types and their respective supply chains. The life cycle inventories are fundamentally based on [19]. The composition of the battery cells is based on the BatPac 5.0 model [15]. Within the models for the battery types, the functional unit is considered so that the material flows, especially from the component production to the cell production, can be derived. For the composition and energy demand of the positive active materials, the GREET 2021 model is used, whereas, for the negative active material, the inventories of Engels et al. are applied as the basis [20,21].

Furthermore, the materials and energy flow data for components and cell production are derived from [22–25]. The activities of the raw material extraction and processing are based on the ecoinvent database, except for the lithium hydroxide routes, which are based on Schenker et al. and Chordia et al. [26,27]. These studies include data for specific locations for lithium extraction and processing and can thus provide more detailed insights into the influence of supplier selection based on the location.

In addition, all the activities in the foreground system are adapted to reflect the current average production shares. For all available countries in the production shares, a country-specific activity is created including the country's average electricity mix, a country-specific sector from the SHDB, or country-specific cost rates for wages, production area, and electricity based on market data and the BatPac 5.0 model. However, since the economic assessment considers the perspective of the battery cell producer, these cost rates are only considered for the activities in the battery cell production phase. The economic assessment of the remaining activities is based on market prices drawn from literature and market reports. Figure 2 illustrates the average production shares for battery cell production in 2021 [28].

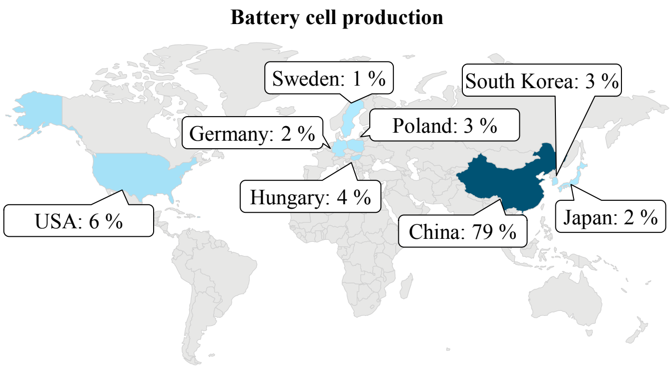

Figure 2: Production shares for battery cell production

Based on the production shares and the country-specific activities, market activities are created, which are then used as inputs for the downstream activities. During the linking of the created activities, transport activities are added to the activities as input flows. These transport distances are based on the distances between the defined countries. Lorries and container ships are assumed to be the primary means of transportation. The distances between the countries are calculated using searates.com. However, if no production share is available for an activity in the foreground system, a global average activity is created using the global average electricity mix and average transport distances.

The activities created based on the global production shares define the baseline scenario. Furthermore, three scenarios with adapted supply chains are investigated in more detail. In the first scenario, the influence of the location on the battery cell production is analyzed. For this purpose, it is assumed that the battery cells are produced to 100% in one of the countries depicted in Figure 2, leading to eight different supply chains to be assessed. A similar approach is applied in the second scenario, where the locations are changed to those countries currently producing the positive active materials. In the case of NMC811, the countries or regions are China, South Korea, Japan, Europe, and others. For NCA, the producing countries are Japan, South Korea, China, and others, while LFP is produced in China, Canada, and the USA [29,30]. The last scenario investigates the influence of different production routes for lithium hydroxide. The three routes reflect the production in Australia, Chile, and China [31].

4. Results and discussion

The results of the selected impact categories are calculated using the Python-based Brightway2 framework [32]. For the environmental impact categories, the indicator scores for the baseline scenario are presented in Table 1. The indicator scores are assigned to the three phases defined in the system boundaries and normalized to a cell capacity of one kWh. Table 1 indicates that the NCA battery performs worst in all four impact categories, while the LFP battery performs best. The difference between these two battery types ranges from 9% for *climate change* to 74% for *metal depletion*. The large difference for the latter is a direct consequence of the materials used in the batteries. In particular, the extraction and processing of nickel and cobalt are associated with high impacts, while the extraction of lithium hydroxide, which is in high demand to produce LFP batteries, is less significant. Compared to this, the difference in material extraction and processing for *climate change* is smaller between the two batteries. Furthermore, for the cell production of the LFP battery, more energy per kWh is required explaining the smaller difference for this impact category. Besides the differences, the results of the environmental assessment reveal that the material extraction and processing phase has the highest indicator scores for all batteries and impact categories except for *climate change*, where cell production has the highest indicator scores in the cases of the NMC811 and LFP batteries. This is due to the high energy demand of the drying processes and the dry room operation.

The phase material extraction and processing also has the highest indicator scores for all investigated battery types and impact categories regarding the socio-economic assessment

Table 1: Results of the environmental assessment

Impact category	Climate change			Metal depletion			Particulate matter formation			Terrestrial acidification		
Unit	kg CO_2-eq./kWh			kg Fe-eq./kWh			kg PM10-eq./kWh			kg SO_2-eq./kWh		
Battery	NMC811	NCA	LFP	NMC811	NCA	LFP	NMC811	NCA	LFP	NMC811	NCA	LFP
Material extraction and processing	42.14	48.25	37.79	71.27	77.72	18.96	0.34	0.37	0.15	1.29	1.40	0.41
Component production	14.44	14.42	7.00	0.46	0.48	1.11	0.03	0.02	0.02	0.06	0.06	0.04
Cell production	46.00	46.72	54.36	0.28	0.28	0.32	0.10	0.10	0.12	0.19	0.19	0.23
Total	102.58	109.39	99.15	72.01	78.48	20.38	0.46	0.49	0.29	1.54	1.65	0.68

(Table 2). This is due to the increased social risks in producing countries such as DR Congo, China, and Indonesia. This also holds for the economic impact, where 86% - 90% of the cost can be explained by materials and components, while the remaining cost is incurred by depreciation, personnel, electricity, and transport.

For the social impact categories, the NMC811 battery has the highest indicator scores, while for the economic impact categories, the NCA battery has the highest indicator score. In terms of the social impact categories, this is a direct consequence of the risks associated with the countries considered. Especially, the positive active material is responsible for the large differences. Since the main producing countries of NCA are South Korea and Japan, the allocated risks are much lower for child labor or forced labor compared to MC811 and LFP, which are mainly produced in China.

Overall, the environmental and socio-economic assessment results highlight the possible trade-offs between impact categories, making it difficult to select the best design for the supply chains in terms of sustainability based on the results of the LCSA. To underline this in more detail and to show the influence of locations, the results of the three scenarios compared to the baseline scenario are explained in the following.

For the first scenario, the highest reduction potential for the environmental indicator scores can be observed for the LFP battery (Figure 3). The highest reduction for *climate change*, *terrestrial acidification*, and *particulate matter formation* can be achieved if the batteries are produced in Sweden. For example, the indicator scores for *climate change* of the LFP battery are more than halved compared to the baseline scenario. This is mainly due to the country-specific electricity mix. In the case of *metal depletion,* no significant changes can be observed since the upstream processes are not changed. Furthermore, the results underline that transport distances have a negligible influence.

Nevertheless, changing the locations for the battery cell production also leads to increasing indicator scores in several cases. If the batteries are produced in China, the indicator scores increase by up to 6%, depending on the cell chemistry and impact category. Furthermore, Poland as producing country of LFP batteries would lead to an increase of the indicator scores by 17% in the case of *terrestrial acidification*, which is a direct consequence of the high share of coal in the electricity mix. However, in the case of *particulate matter formation*, the indicator scores would decrease if the batteries were produced in Poland, highlighting possible conflicts for the design of sustainable supply chains.

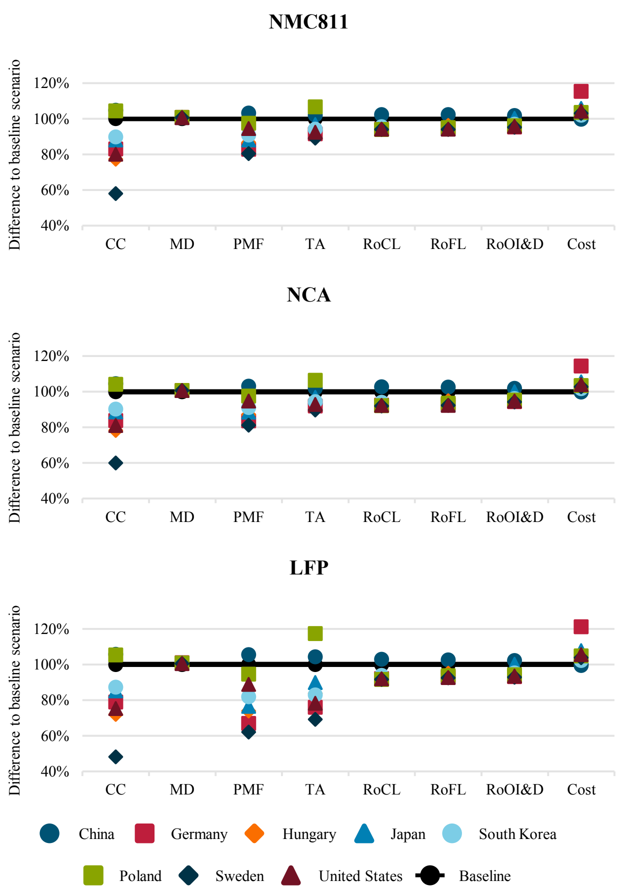

Figure 3: Changes to the baseline scenario for the first scenario

For the social impact categories, comparable effects can be observed as for the environmental impact categories. In the cases of *risk of child labor*, *risk of forced labor*, and *risk of occupational injuries and deaths,* the medium risk hours decrease between 4% and 8%, except for China and Japan. If the batteries are produced in China, the medium risk hours increase by 2% to 3%. Furthermore, if the batteries are produced in Japan, the *risk of occupational injuries and deaths* would not change.

For *cost*, the opposite can be noted. If the batteries are made in China, the cost will decrease slightly. In all other cases, the cost will increase, especially if the batteries are produced in Germany. For example, for LFP production in Germany, the cost would increase by 21%, which can be explained by the higher electricity and personnel cost. Therefore, this scenario reveals that the selection of a location in Germany could be beneficial from a social and environmental perspective but would be unfavorable from an economic perspective.

Table 2: Results of the socio-economic assessment

Impact category	Risk of child labor			Risk of forced labor			Risk of occupational injuries and deaths			Cost		
Unit	medium risk hours/kWh			medium risk hours/kWh			medium risk hours/kWh			US-Dollar/kWh		
Battery	NMC811	NCA	LFP	NMC811	NCA	LFP	NMC811	NCA	LFP	NMC811	NCA	LFP
Material extraction and processing	182.20	196.91	188.31	334.23	354.87	377.04	186.42	206.15	186.80	51.10	56.07	56.58
Component production	99.45	28.90	57.29	151.40	40.83	89.65	108.70	53.91	56.68	46.82	48.08	24.51
Cell production	20.98	21.77	24.93	36.32	37.59	43.30	19.60	20.31	23.34	10.78	11.18	12.76
Total	302.63	247.57	270.53	521.95	433.29	509.98	314.73	280.38	266.82	108.70	115.33	93.85

The results of the environmental assessment of the second scenario indicate that the locations have a smaller influence on the indicator scores assigned to the production of the positive active materials (Figure 4). This depends mainly on the assumed production process. In the case of LFP, heat from natural gas is used as energy input, leading to no differences for the selected countries. Since the production of NMC811 and NCA also consumes electricity, small effects on the indicator scores can be observed for *climate change*, *particulate matter formation*, and *terrestrial acidification.* For the *metal depletion*, no noteworthy reduction of the indicator scores can be achieved.

Nevertheless, for the social indicator scores, the differences are higher. For example, the *risk of forced labor* can be reduced by 21% - 23% if NMC811 is produced in Japan or South Korea instead of China, where the material is mostly produced in the baseline scenario. Also, for the LFP production, similar findings can be derived. However, this effect can not be observed for NCA since Japan and South Korea are already the main producing countries in the baseline scenario so that no high reduction potentials can be shown with the considered locations. However, the risks would increase significantly if the positive active material is produced in China. Only neglectable changes can be monitored for the impact category *cost* depending on the changing transport distances. This depends on the assumption that the costs are considered from the perspective of the cell producer, and in this way, the prices for the active materials are independent of the location.

This is also true for the third scenario. However, the location to produce lithium hydroxide significantly influences the results of the environmental and social assessment (Figure 5). In terms of *climate change*, *terrestrial acidification*, and *particular matter formation*, the emissions can be reduced between 5% and 8% if the lithium hydroxide for the LFP battery is produced in Chile. Also, the production of lithium hydroxide in Australia would lead to improvements of around 2% - 3% in the case of LFP, whereas the production in China would lead to a rise of up to 11%. These differences are mainly explained by the country-specific electricity mix and how lithium is extracted. Additionally, the higher share of lithium hydroxide leads to a higher influence through the location selection for the LFP battery. In the case of *metal depletion*, the influence of the different locations is neglectable, which underlines the findings in the baseline scenarios.

For the social impact categories, the influence is even higher compared to the environmental assessment. Especially with the production in Australia, considerable risk reduction can be achieved. For example, if lithium hydroxide for the LFP is produced in Australia, the medium risk hours could be reduced by 32% for the impact category *risk of child labor*. Also, the production in Chile would lead to high improvements, while the production in China would lead to higher or similar medium risk hours compared to the baseline scenario.

5. Conclusion and outlook

In this study, the supply chains of three batteries are investigated in terms of their environmental, economic, and social impacts using an LCSA. A baseline scenario is created

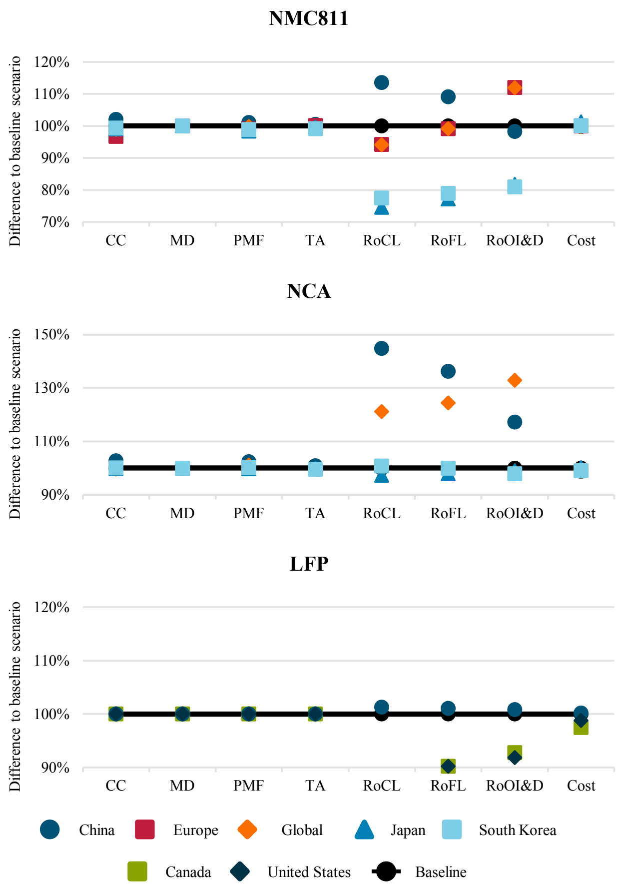

Figure 4: Changes to the baseline scenario for the second scenario

to investigate the effect of different locations on the results. In the baseline scenario, the global production shares are considered for the different activities from material extraction and processing to cell production. The baseline scenario is compared to three additional scenarios. In these scenarios, it is assumed that only one country produces the battery cells, positive active materials, or lithium hydroxide.

For the baseline scenario, the results show that the LFP battery is favorable from an environmental perspective, while the supply chain of the NCA battery has the highest environmental indicator scores. In terms of cost, the LFP seems also favorable. However, for two of three investigated social impact categories, the NCA battery has the lowest indicator scores, while the NMC811 battery has the highest indicator scores. These findings underline the possible trade-offs between impact categories of different sustainability dimensions. Furthermore, the results show that there could also be trade-offs between the impact categories of one dimension, as shown for the social dimension in the baseline scenario.

Besides, the investigated scenarios have shown that the locations can significantly influence the results of all three sustainability dimensions, whereby the effect can vary depending on the considered locations and processes. Consequently, these results highlight that it is necessary to select the supplier with caution, for example, to comply with the mentioned legal regulations.

However, the stated trade-offs make it difficult to design sustainable supply chains based only on the LCSA results. A solution for this can be implementing a multi-criteria decision-making model that uses the created LCSA results as a starting

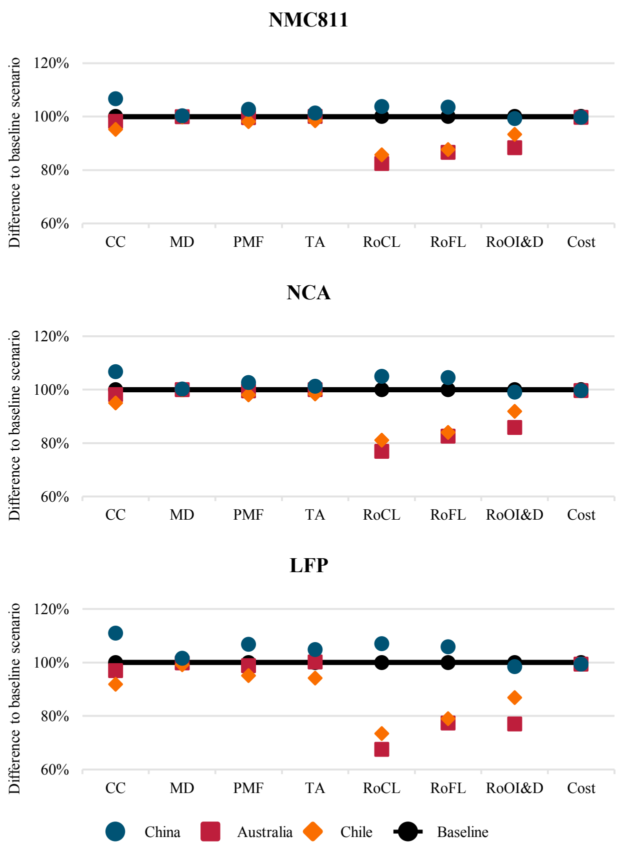

Figure 5: Changes to the baseline scenario for the third scenario

point extended by restrictions such as CO_2 thresholds or capacities to derive recommendations for the design of sustainable supply chains.

For this purpose, this study must be extended in terms of various aspects. First, this study was limited to a cradle-to-gate assessment. However, the recycling of batteries can significantly affect the practical design of sustainable supply chains [33]. Thus, the scope of the study has to be broadened. Furthermore, the assembly of battery modules and packs must be included. Another influential parameter can be the composition and design of the battery cells. Therefore, this should also be investigated in more detail, how this affects the investigations and the respective design of battery supply chains. Potential future locations representing the trend toward more local production of materials and components must also be included in the LCSA when planning battery supply chains.

Regarding the economic assessment, the perspective was limited to the battery cell producer. However, the cell and car producers aspire to integrate supply chains. This can affect the prices they have to pay for materials, as they then have more control over the processes and cost structure. Therefore, the respective routes must be studied more extensively regarding their cost. In addition, further life cycle inventories for describing these processes must be created to reflect the spatial differences in more detail since, e.g., the ore grade can have a high influence on the required process energy [34]. This also underlines the high uncertainties of the results since they depend on several parameters.

Moreover, the social assessment is based on data from the SHDB, which can sensitize stakeholders to potential risks in a particular sector in a country. However, for a detailed assessment of a company's or supplier's social impact, on-site investigations are required.

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