

Article

A Critical Assessment of the Resource Depletion Potential of Current and Future Lithium-Ion Batteries

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Abstract: Resource depletion aspects are repeatedly used as an argument for a shift towards new battery technologies. However, whether serious shortages due to the increased demand for traction and stationary batteries can actually be expected is subject to an ongoing discussion. In order to identify the principal drivers of resource depletion for battery production, we assess different lithium-ion battery types and a new lithium-free battery technology (sodium-ion) under this aspect, applying different assessment methodologies. The findings show that very different results are obtained with existing impact assessment methodologies, which hinders clear interpretation. While cobalt, nickel and copper can generally be considered as critical metals, the magnitude of their depletion impacts in comparison with that of other battery materials like lithium, aluminum or manganese differs substantially. A high importance is also found for indirect resource depletion effects caused by the co-extraction of metals from mixed ores. Remarkably, the resource depletion potential per kg of produced battery is driven only partially by the electrode materials and thus depends comparably little on the battery chemistry itself. One of the key drivers for resource depletion seems to be the metals (and co-products) in electronic parts required for the battery management system, a component rather independent from the actual battery chemistry. However, when assessing the batteries on a capacity basis (per kWh storage capacity), a high-energy density also turns out to be relevant, since it reduces the mass of battery required for providing one kWh, and thus the associated resource depletion impacts.

Keywords: battery; energy storage; environmental impact; life cycle assessment; lithium-ion; resource depletion; sodium-ion; system analysis

1. Introduction

Driven by the transition towards a low-carbon economy, the demand for electrochemical energy storage, especially batteries, is increasing steadily [1,2]. Renewable energy is principally available in the form of electricity with high fluctuations, creating the need for energy storage for grid buffering purposes and for storing electricity as fuel for electric vehicles. The increasing demand for batteries goes along with an increasing demand in materials, especially metals, required for their production [3–5]. Thus, doubts have repeatedly been expressed questioning the sustainability of electric mobility and stationary storage systems based on lithium-ion batteries (LIBs) due to the required resources [6–8]. In fact, the potential lithium scarcity is often used as an argument for a shift towards new battery chemistries (“beyond LIBs”), e.g., a sodium-ion battery (SIB) [9,10]. Nevertheless, the availability of lithium may be less problematic than expected. Several studies have already been released on this issue and come to very different conclusions [3,6,7,11,12]. The majority of these studies rely on life cycle assessment and material flow analysis for assessing the resource depletion potentials. The latter

quantifies the existing mass streams in the existing economic system, and the former tries to link these with an actual impact, i.e., the environmental consequences of these flows on global resource availability. Although life cycle assessment (LCA) is a standardized and established methodology for quantifying the environmental performance of products, goods or services over their whole life cycle [13,14], different methodologies exist for quantifying it (life cycle impact assessment; LCIA) [15]. Due to this fact, there is an ongoing discussion within the LCA community about how to assess resource depletion in LCA and whether resource depletion itself can be considered an environmental issue at all, or if it is rather an economic problem) [16,17].

However, it is considered important to obtain a first rough picture of the main drivers for resource depletion impacts of battery production. Providing an idea about the most critical components and materials of common LIBs under this aspect would help to develop future batteries with minimized impacts on resources. Still, no study is available that compares the most common existing LIB chemistries among each other under resource depletion aspects. Existing studies only assess one or two single-LIB chemistries, but not all at once. Additionally, results cannot be compared between different studies due to the very different assumptions regarding battery layout and other key parameters of the battery manufacturing process. This paper compares the resource depletion potential (RDP) obtained with the most current LCIA methods for LIBs and for a post-lithium battery (sodium-ion battery; SIB). The results obtained for the different battery types and with the different LCIA methods are contrasted in order to obtain some general conclusions/recommendations that can be given in agreement with all existing LCIA methods.

2. Materials and Methods

2.1. Assessment Framework and Common Inventory Database

The results of existing life cycle assessments of LIBs cannot be directly compared among each other because of the very different inventories used by them (different battery layouts and battery configurations are assumed). For a sound evaluation of different LIBs under resource depletion aspects, a common base for assessment is therefore required. This is achieved by recompiling the available life cycle inventories (LCI) from the five principal LCA studies about LIBs and by setting them on a common base [18,19]. Thus, all batteries are assumed to have the same layout (pouch cells in a polypropylene (PP) package). This increases the comparability, while other configurations—e.g., the use of 18650-type round cells instead of pouch cells—would produce different results. The considered LIB chemistries and the corresponding reference works are the following:

- LFP: Lithium-Iron-Phosphate—(LiFePO₄) (Zackrisson et al. [20] and Majeau-Bettez et al. [21])
- LFP-LTO: LFP with Lithium-Titanate anode—(LiFePO₄-Li₄Ti₅O₁₂) (Bauer [22])
- LMO: Lithium-Manganese-Oxide—(LiMnO₂) (Notter et al. [23])
- NCA: Lithium-Nickel-Cobalt-Aluminium-Oxide—(LiNi_{0.8}Co_{0.15}Al_{0.05}O₂) (Bauer [22])
- NCM: Lithium-Nickel-Cobalt-Manganese-Oxide—(LiNi_{0.33}Co_{0.33}Mn_{0.33}O₂—Majeau-Bettez et al. [21] or LiNi_{0.4}Co_{0.2}Mn_{0.4}O₂—Ellingsen et al. [24])

As in the underlying studies, the batteries are assumed to be traction batteries for electric vehicles. The mass shares of the basic battery components and the principal materials they are made of are given in Table 1. The components that have been modified (set on a common base) are marked with an asterisk; all remaining parameters are taken over identically as given in the original LCI of the underlying studies. In order to also include a post-lithium battery, the LCI for a layered oxide sodium-ion battery based on the work of Peters et al. [25] is also set on the same common base and assessed together with the LIB in order to check the advantages of a lithium-less battery type under resource depletion potential (RDP) aspects. The energy densities of the batteries are also given in Table 1, since they change with the recompiled inventories. In order to obtain these, the “dead mass” of the battery (BMS and package) is determined in the original inventories and in the recompiled inventories. Based on these two values, the energy density with the modified layout is calculated.

Implementation and results calculation is done in open LCA [26], using different life cycle impact assessment (LCIA) methods. The assessment follows a cradle-to-gate perspective and therefore covers the battery production process until the factory gate, including all upstream processes. Battery use phase and end-of-life handling are excluded in order to focus explicitly on the material demand for a new battery. This provides a comprehensive picture about the critical materials within the battery and thus the materials on which a recycling process should focus. On the other hand, it does not represent the actual resource depletion impacts of an LIB industry, where at least a small share is already recycled, reducing RDP impacts. Nevertheless, current return rates for LIBs are still low [27] and no large-scale recycling processes have been established yet, which is why very little information is available regarding the potential differences in recyclability of the different battery chemistries. Thus, modelling the entire end-of-life chain is considered to introduce, rather than reduce, additional uncertainty. The assessment is done on a mass basis (i.e., the functional unit as a basis for comparison is 1 kg of battery pack), but the results are also discussed on a capacity basis (1 kWh of storage capacity), in order to consider the potentially different energy densities between battery types and their influence on the results.

2.2. Resource Depletion Impact Assessment Methodologies

In order to obtain an exhaustive picture of the potential resource depletion impacts, six different life cycle impact assessment (LCIA) methodologies are applied for quantifying the RDP impacts of resource depletion:

CML (with the three different reserve estimations; CML-er, CML-rb, CML-ar) [28]: CML uses a reserve base approach, which sets the current extraction rate in relation to the globally available stocks and thus calculates an RDP factor. Here, the estimation of the actually available resources is the critical aspect, and CML therefore provides three different bases for RDP quantification: (i) the economic reserve (amount of resources that can be obtained economically today; CML-er); (ii) the reserve base (amount of resources whose exploitation is technically feasible; CML-rb); and (iii) the absolute reserve (content of the resource in earth's crust; CML-ar). Since these three reserve bases already vary strongly, very different results can be obtained depending on which reserve base is used for assessment. The ILCD handbook (International Reference Life Cycle Data System; reference guidelines for LCA practitioners published by the European Commission's Joint Research Centre) currently recommends the use of CML-rb (reserve base) as a methodology for assessing resource depletion [15].

EI99 and ReCiPe: ReCiPe [29] and EcoIndicator99 (EI99) [30] use approaches based on the additional effort required by future generations for extracting a certain resource as a result of the reduced ore concentration due to today's exploitation of the higher concentrated ores. ReCiPe quantifies this additional effort in economic terms (additional costs), while EI99 uses an energetic approach (additional energy required for extraction). While these approaches are principally endpoint-oriented, midpoint characterization factors (CF) are also provided, in the case of ReCiPe as a substance equivalent; iron equivalents (Fe-eq). Both cover a significantly lower number of substances (12/20) than CML (49), cf. Table 2.

AADP: The anthropogenic stock extended abiotic depletion potential (AADP) methodology [31,32] tries to overcome one of the principal criticisms about resource depletion assessment, the fact that extracted resources are not unavailable when used for a product, but rather form part of the so-called anthropogenic stock. From there, they can be recovered more or less easily after the end-of-life of the product in which they are contained. Only when the product is disposed of might this stock end up in a landfill or be dissipated into the environment in other ways, from where recovery may no longer be feasible (basically due to too-low concentrations). Thus, not only extractable reserves in the ground, but also the amount of resources in use in the economy are considered for estimating the total reserves. This would reduce the impacts obtained, for example for gold, with a comparably high anthropogenic stock accumulated, but limited extractable reserves. The estimation of available resources is based on

the ultimately extractable reserves, assuming that 0.01% of the total amount of carrier metals in earth's crust up to a depth of 3 km will ultimately be available, and 0.001% for co-elements.

Table 2. Different resource depletion potential (RDP) assessment methods and comparison of characterization factors (CF) for selected key battery materials, relative to iron (i.e., for each methodology, the CF for the different metals are divided by the CF for iron, providing an RDP impact relative to that of iron, which eases comparison). Note that the values are relative values and are therefore unitless. The units are nevertheless displayed for completeness purposes. * Coverage = Number of substances covered by the methodology (only metals and minerals; excl. fossil fuels); ** 30 elements and 34 minerals.

Method.	ReCiPe	EI99	CML-ar	CML-rb	CML-er	AADP	CExD	EcoSc
Orig. unit	(kg Fe-eq)	(MJ)	(kg Sb-eq)	(kg Sb-eq)	(kg Sb-eq)	(kg Sb-eq)	(MJ)	(UBP)
Al	0.09	46.67	0.02	15.24	5.88	0.01	2.27	3.55
Co	1.01	–	299.12	15,405.80	13,459.71	37,818.18	76.39	5263.16
Cu	42.69	719.61	26,043.70	1506.01	1083.86	19,672.73	35.85	131.58
Fe	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Li	–	–	218.6	8001.2	12,042.9	88.0	0	473.7
Mn	76.61	6.14	48.43	14.12	159.57	2752.73	1.76	103.95
Mb	207.51	803.92	338,766.08	42,783.94	40,104.64	224,363.64	574.29	7631.58
Ni	12.53	465.69	1244.95	2513.73	4638.59	1101.82	24.04	842.11
Sn	1271.31	11,764.71	309,449.27	69,436.23	21,364.01	55,272.73	250.00	30,263.16
Zn	2.25	80.20	10,259.19	2195.85	2214.67	3127.27	2.69	605.26
Coverage *	20	12	49	49	49	30 + 34 **	31	48

CExD: The Cumulative Exergy Demand (CExD) [33] uses a thermodynamic approach, the exergy content of a mineral as an indicator of its scarcity. The chemical exergy of a (non-energy carrying) mineral is determined by its enthalpy of formation and its concentration in a deposit in comparison with the background concentration (entropy) and can thus be considered a good proxy for its availability. It is also based on objective thermodynamic principles and is therefore independent from changes in reserve estimations due to new technology or varying prices. The cumulative exergy demand is obtained in MJ.

EcoSc: The Ecological Scarcity Method (EcoSc) [34] has a Swiss focus and uses a distance-to-target approach that quantifies environmental impacts based on policy recommendations. That means it quantifies the (non-) contribution of a process for achieving a political target, i.e., a sustainable consumption level on a global scale. Applied to energy resources, this target is a 2000-watt society, and applied to resources, a “footprint one” is aspired. Since no critical flow (=no sustainable consumption target) has yet been established for minerals and metal extraction, maintaining the status quo is set as the interim target, i.e., maintaining current extraction levels. EcoSc quantifies the impact in UBPs (Umweltbelastungspunkte / environmental burden points).

Apart from using different approaches for modelling the impacts of resource depletion, these methodologies also cover very different amounts of substances. Table 2 gives an overview of the amounts of substances covered by each of the methodologies and the characterization factors for selected key materials for LIB production, relative to a common reference substance, iron. The unit in which the RDP is quantified by each methodology is also indicated in Table 2, although the values are relative values and therefore unitless, which notably improves the comparability of the methodologies. EI99 and ReCiPe cover a significantly lower amount of substances, which reduces their general applicability for assessing resource depletion. The different characterization factors vary substantially, up to several orders of magnitude for some substances.

3. Results

3.1. Resource Depletion Impacts of Battery Production

The resource depletion impacts obtained with the different impact assessment methodologies for the production of 1 kg of LIB are given in Figure 1 and discussed in the following. The impacts

per kWh of energy storage capacity are provided and discussed later on (Figure 2), which allows for comparing the assessed batteries considering their different energy densities.

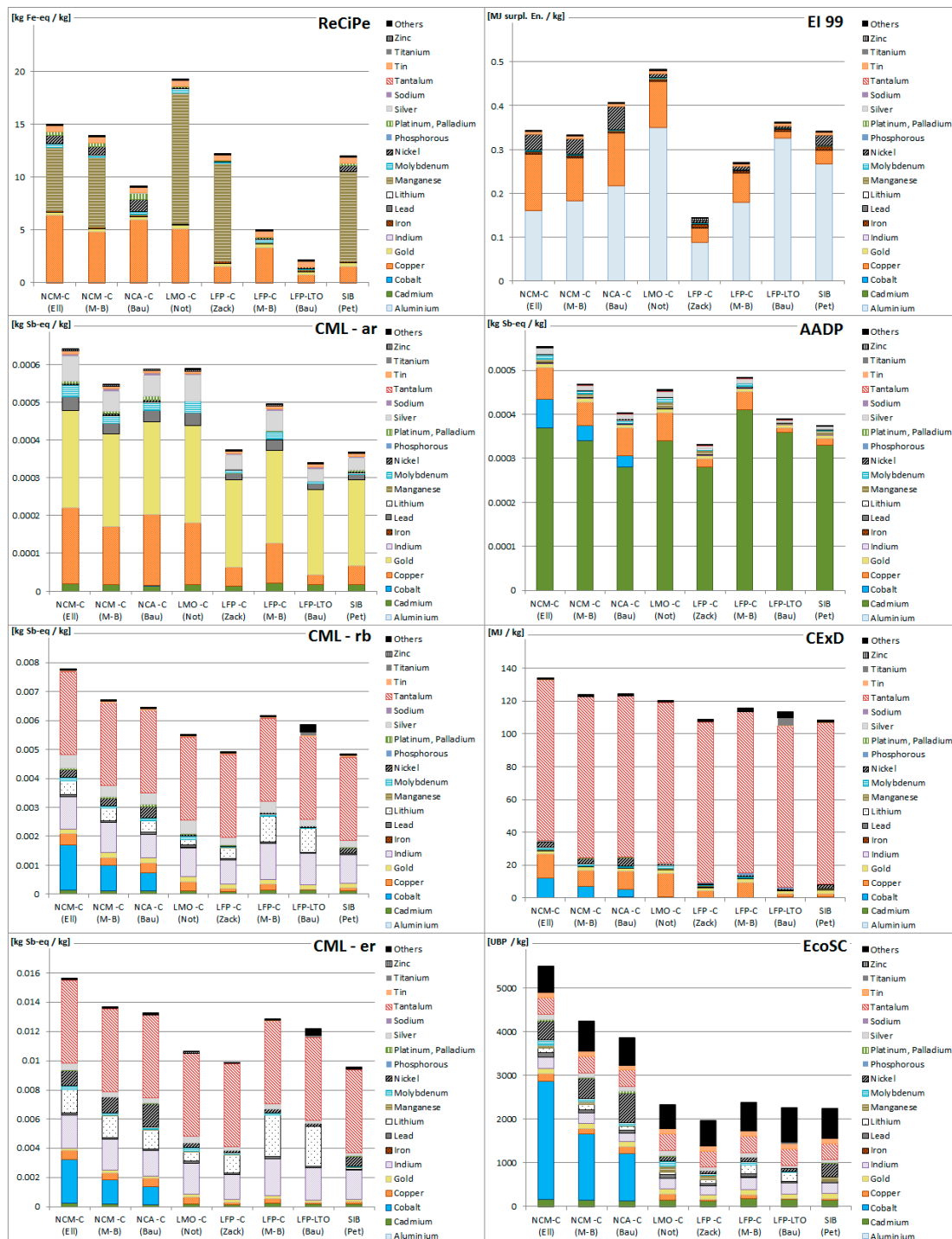


Figure 1. Contribution of materials to the RDP impact of different types of LIBs. Unit of comparison is 1 kg of produced LIB.

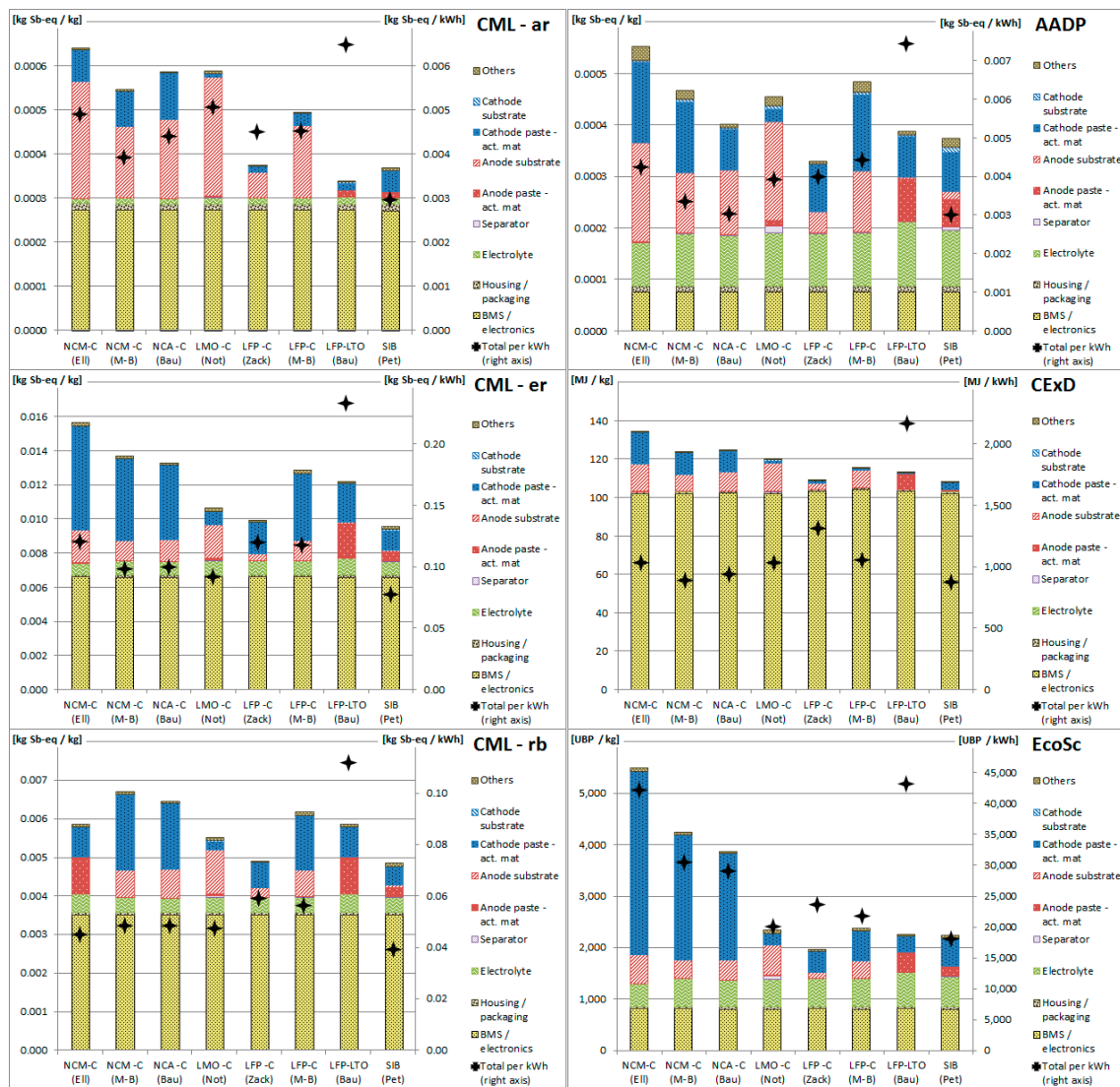


Figure 2. Contribution of battery components to the RDP impact of different types of lithium-ion batteries (LIB). Unit of comparison is 1 kg of produced LIB (mass basis; left y-axis). Black stars display the total impact per kWh (capacity basis; right y-axis) for comparison.

ReciPe is based on the surplus costs for extracting future minerals. It is clearly dominated by manganese, giving high impacts to all manganese-containing battery chemistries (NCM, LMO), but also to the LFP battery as modelled by Zackrisson et al [20]. The latter is an effect of the proxy used by Zackrisson et al. for the LFP active material precursor. They assume the precursor to be ferrite, and use ferrite for cathode tube production from the ecoinvent database as a dataset, which actually represents manganese-ferrite and thus contains important amounts of manganese. The high impact given to manganese by this methodology is questionable, manganese being a comparably abundant and cheap material. Apart from that, copper shows important contributions (interestingly with a very similar share to the total impacts as obtained for the CML-ar), and, to a much lower extent, nickel and tin (the latter required for soldering of electronic components within the BMS).

EI99, based on the surplus energy required for extracting future resources of lower concentration/quality, gives a very high weight to aluminum. In fact, aluminium production is very energy-intensive, but one of the most abundant minerals. Increased energy intensity would increase impacts associated with extraction, but do not need to be a resource problem itself for a comparably abundant resource. Additionally, they might be a minor issue for future energy based mainly on

renewables. Al is responsible for over 50% of the resource depletion impacts for all battery chemistries, followed by copper and nickel. Other materials play only a very small role.

CML-ar (absolute reserve/CML baseline) takes as a reference the content of a resource in earth's crust and gives a high weight to precious metals like gold and silver, but also to copper. Thus, the current collectors, but even more, the electronic components contained above all in the BMS, dominate the resource depletion impact. The BMS is assumed to be the same for all batteries and the impacts caused by it are—on a mass basis—identical across all battery types. Therefore, current collectors are the main driver for differences between batteries, with significantly different mass shares assumed for them by the underlying studies. Lead, molybdenum and cadmium are also relevant contributors to RDP, though not contained directly in the batteries. This is an indirect resource depletion effect, caused by the fact that many ores contain more than one metal, and mining of one of them causes the depletion also of the other metals contained in the ore (mining coproducts). The environmental burdens (and thus also the resource depletion impacts) of the mining activity are then usually allocated to the co-products according to economic criteria. The same applies to the copper demand, where a relevant share is not caused by the direct need for copper in the battery, but for nickel. Again, nickel is co-produced together with copper, and the nickel mining also leads to the extraction of copper resources. This can be observed best for the SIB, which contains significantly lower amounts of copper than most LIBs (except LFP-LTO, due to the use of aluminum current collectors in the anode), but still shows a significant RDP impact from copper, which is mainly caused by the nickel required for the cathode material.

CML-er and CML-rb show very similar results and the contribution of the different battery materials to the total resource depletion impact is also similar. Remarkable are the contributions of tantalum and indium, which are both non-battery materials in the narrower sense. Tantalum is required for electronic components within the BMS, primarily tantalum capacitors. With a characterization factor for tantalum about half that of gold, a high sensitivity on the use of this type of capacitor is given, and the chosen BMS model gives a very high score. Thus, the BMS modelling has to be done carefully, with small electronics components showing potentially very high impacts. Indium, also associated with a very high score for this methodology, is a co-product of copper and nickel mining. While not contained directly in the batteries, its extraction is driven indirectly by the copper and nickel demand. Apart from that, the direct demand for nickel and cobalt, but also the different amounts of lithium required for each battery chemistry, are the main sources for differences between battery chemistries. In fact, lithium is one of the main contributors to RDP for the cobalt- and nickel-free battery types, while NCM and NCA show higher impacts basically due to the use of nickel and cobalt. The different contributions from lithium originate in the different modelling of the batteries (different amounts of active material and of electrolyte).

AADP, which follows a dissipation-based approach, is clearly dominated by cadmium, which itself is also a non-battery material, but rather (like indium) co-produced together with zinc in zinc mines. Neither cadmium nor zinc are contained directly in the modelled LIBs, but significant amounts of sulfuric acid are required in the production processes, which again is a by-product of zinc mining: Theecoinvent dataset “market for sulfuric acid,” used as a background dataset for sulfuric acid, contains a small share of acid proceeding from zinc mining (the SO₂ from the ore roasting is recovered as H₂SO₄ and sold on the market as by-product). This small share of sulfuric acid proceeding from zinc mines causes the high cadmium-driven resource depletion, due to the allocation of part of the cadmium extraction to the by-product sulfuric acid. Other important contributions are obtained for copper and cobalt, and, to a much lower extent, for precious metals like gold and silver, and for molybdenum.

CExD gives a picture similar to CML-ar, with tantalum dominating the total impacts even more, while giving less weight to indium and lithium. Actually, lithium accounting is one of the shortcomings of the CExD method, with lithium in brine being accounted for with zero exergy. This can be considered an underestimation, since the concentration of lithium in brines is significantly above the average ambient concentration or the concentration in seawater. Similar to CML-ar, copper, cobalt and nickel

are (excluding tantalum) the most relevant metals for the total impact, with minor shares contributed by gold, silver and molybdenum.

EcoSc: While the general picture is roughly comparable to the one obtained with CML-ar and CExD, the first thing that catches attention is the high contribution from “others,” i.e., materials that are not apparently related to battery production. These are mainly base rock minerals like fluorspar and gravel, making up 6%–22%, and 2%–5% of the total impacts, respectively. The high contribution of these materials is a result of the particular Swiss focus of the methodology; gravel and rock availability are limited due to land-use-change restrictions and thus the exploitable reserves are very small compared to the actually existing ones. Fluorspar is required as a precursor for hydrogen fluoride production, which itself is a precursor for LiPF_6 and therefore driven by the electrolyte, while gravel is used for calcium carbonate production and for infrastructure. Apart from that, cobalt plays a very important role, more than in other methodologies, but so do nickel, tantalum and indium, followed by copper, cadmium, lithium, molybdenum and tin.

In general, the results obtained with each of the varying LCIA methods are quite different, even for the CML indicator when using the different resource bases. Only the CML-er and CML-rb show a similar picture. Depending on the applied methodology, totally different materials drive the resource depletion impacts. Nevertheless, it has to be kept in mind that these are impacts per kg of battery, and that NCM and NCA typically show higher energy densities, while LFP-LTO show significantly higher lifetimes. Thus, the results would change when looking at the batteries under aspects of energy density or lifetime storage capacity [18]. Considering the life cycle of the different battery types would require a different approach, including the use phase of the battery, and is therefore beyond the scope of this study. However, a comparison on a storage capacity basis is quite straightforward, dividing the impacts per kg by the energy density. For this purpose, the energy densities of the battery packs as provided by the underlying studies are re-calculated considering the assumed mass composition according to Table 1, and the corresponding impacts per kWh are determined. The energy densities and the impacts on a storage capacity basis obtained in this way are provided in Figure 2 as black stars (right *y*-axis). The importance of a high energy density becomes evident, with LTO now scoring worst with all LCIA methodologies. Their low energy density requires significantly more battery mass to be produced, increasing the corresponding RDP impacts. The SIB is among the best scoring batteries, except for ReCiPe and EI99, but it must be taken into account that the energy density assumed by the underlying study is not yet achieved by “pre-industrial” scale prototypes [35]. Apart from that, the differences between the battery chemistries are comparably small and depend rather on the applied methodology, which is why no recommendation seems possible in this regard. The lower cobalt content of the NCM^{424} battery generally gives it few advantages compared to the NCM^{333} , cobalt being associated with high RDP impacts with the majority of the applied methodologies. The key drivers for RDP impacts in the different LCIA methods are discussed in the following.

3.2. Resource Depletion Impacts of Battery Components

The contribution of the principal battery components to the total resource depletion impact is displayed in Figure 2. Due to their low coverage, ReCiPe and EI99 are not included in Figure 2 (the suitability of the different methodologies for assessing RDP of battery production is discussed further in the next section). The high relevance of the electronics parts/the BMS can be observed clearly. Across all methodologies, it contributes significant shares to the total RDP impact, in spite of its relatively low mass share of 4.7% within the battery packs (see Table 1). This is driven principally by the tantalum capacitors (CML-eco, CML-rb and CExD) and other precious metals like gold and silver, but also copper parts. The tantalum content of the BMS is only 0.53%, but responsible for between 50% (EcoSc) and 95% (CExD) of its RDP impacts. The varying relevance given to copper by the different methodologies can be seen very well when looking at the anode substrate, which is made of pure copper (except LTO and SIB, where aluminum can be used also for the anode current collector). Here, AADP and CML-ar give the highest impacts. Nevertheless, this is not only due

to the direct depletion of copper resources, but also of the co-mined metals like cadmium, zinc or lead, which are often also contained in sulfidic ores. Comparably high contributions are obtained with AADP and EcoSc also for the electrolyte, which is driven by two substances: (i) the demand for fluorspar for hydrogen fluoride as a precursor for hexafluorophosphate production (only EcoSc; here making up $\frac{3}{4}$ of the electrolyte's impact); and (ii) the sulfuric acid required for hydrogen fluoride production. Here, a small share is sourced from zinc and lead mines, where the SO₂ emitted by the roasting process is partially recovered as H₂SO₄, a valuable by-product sold on the market. Mining impacts (and also corresponding RDP impacts) are allocated according to economic considerations also to the sulfuric acid co-product. Since zinc and lead ores also contain cadmium, this leads, together with the high sensitivity of AADP on cadmium depletion, to the high RDP contribution of sulfuric acid. Correspondingly, all battery components that require sulfuric acid for their production cause relevant RDP impacts with this methodology. This demonstrates very clearly the problem of allocating RDP impacts for mixed ores, as discussed more in detail in the following. The contribution of the cathode active material on the other hand is rather self-explanatory, since the corresponding RDP impacts are mainly caused by their intrinsic metal content (their stoichiometric composition), and can therefore be mapped quite directly to the RDP impacts of lithium, nickel, cobalt and manganese according to Figure 1.

3.3. Applicability of Methodologies for Battery Assessment

ReCiPe and **EI99**, while showing interesting approaches, seem to be little suitable for assessing the resource depletion potential of LIB production. The extraordinarily high contributions of aluminium (EI99) and manganese (ReCiPe), the third and 12th most abundant elements in earth's crust [36], make the interpretation of results difficult and mask the contributions of other elements partially. Apart from that, they have a very limited coverage and do not quantify the depletion of some key materials for LIBs, such as lithium (both) or cobalt (EI99). When disregarding the impacts caused by aluminium and manganese demand, the results are fairly in line with other methodologies, with the remaining principal contributors being copper, nickel, tin, and the precious materials needed for the BMS, above all, gold and silver. In general, these two methodologies based on surplus effort for future extraction cannot be recommended for assessing battery systems, since they do not reflect actual resource availability.

The **CML** methodology, based on an absolute reserve depletion approach, shows the importance of the reserve estimation, with fundamentally different results obtained by CML-ar and CML-rb/CML-er. While the latter two (reserve base and economic reserve) use the (technically and economically) exploitable reserves as a basis, the absolute reserve (CML-ar) uses the crustal content of a resource as the ultimate limit of resource availability. The latter has the advantage of being a fixed value independent from economic and technological considerations, but has limited significance, since it can never be mined completely. For instance, the comparable high absolute amounts of lithium in seawater are practically unavailable, the concentration being too low to ever be recovered completely. The economic reserve or reserve base considers this and only accounts for actually exploitable reserves. These are rather subjective and change with technology and therefore with time, but are still more significant for the actual practical availability than the crustal content. Under this aspect, lithium becomes a relevant contributor to the overall resource depletion potential of LIBs, situated between nickel and cobalt. An advantage of the CML methodology is also its broad coverage, quantifying the RDP impact of 49 substances. While not all 49 are actually relevant for assessing LIBs, still, 32 of them contribute to the total RDP impact, pointing out the importance of providing a broad set of CFs, especially for complex products like LIBs that are composed of numerous components from very different materials.

AADP quantifies not the amount of resource extracted, but the amount of the resource dissipated, i.e., lost to the environment. This accounts for the fact that a metal does not become unavailable due to its extraction, but is still available in the economy (forming the anthropogenic stock).

While AADP is a very interesting approach, it might need some revision of the reserve base estimation, with the extremely high contribution of, in particular, cadmium skewing the results significantly and making interpretation difficult. Apart from that, it shows qualitatively similar results to those obtained with CML-rb and CExD when disregarding the two extreme contributors, cadmium (for AADP) and tantalum (CML and CExD). Nevertheless, the implementation of AADP in the current ecoinvent database can be considered insufficient, since it would require assigning RDP characterization factors to outputs (emissions, i.e., dissipation), not to inputs. This is not the case, and the AADP characterization factors are still mapped to resource flows (inputs), which is why the obtained results do not fully reflect the original idea of AADP. As a workaround solution, all materials recovered from the recycling of the assessed product could be accounted for as negative resource extraction. In sum, this would then account for only the actually dissipated amounts of materials, giving a more realistic picture close to the original idea of AADP. In any case, this would not be possible for cradle-to-gate assessments such as the present one. Obviously, using the AADP approach in a consequent way would give a higher weight to the end-of-life handling of products and require thorough modelling of waste streams and waste treatment/recycling processes, but also an appropriate selection of the system model. This is often not the case, and a general lack of information is given in this regard. More work would need to be done on modelling waste streams, recycling processes and the quality of the recovered materials (i.e., their substitutability).

The cumulative exergy demand (CExD) accounts for mineral scarcity by using a thermodynamic approach. The chemical exergy is higher for elements that are less abundant and available in lower concentrations, giving higher impact for less-available minerals. The results obtained with CExD are qualitatively similar to those obtained with CML-rb/CML-er, which underlines the relevance of these approaches for RDP quantification. CExD is considered a very objective and independent method, based on thermodynamic principles and, therefore, not dependent on different reserve estimations, even due to new technology or varying prices. However, the example of Li exhibits that this method strongly depends on the used values for concentration in a given deposit in comparison with the background concentration. The selection of this deposit and the determination of its average metal content are subject to a certain subjectiveness, which is also true for the determination of the background concentration. Hence, while a thorough revision of the characterization factors for key battery elements like lithium or tantalum would be recommendable, it can be considered a promising approach for assessing resource depletion. As for CML, the broad coverage of this methodology can be highlighted, covering not only the most common elements, but also basic minerals like rock or sand (unlike any other methodology). This reduces the risk of “overlooking” (not quantifying) a potentially relevant substance and therefore gives more reliable results in terms of exhaustiveness.

The applicability of EcoSc, a distance-to-target approach based on policy recommendations, is limited slightly due to the explicitly Swiss perspective, with a high impact from base rock mining like gravel or fluorspar. This represents specific Swiss legislation rather than actual resource scarcity. Nevertheless, when disregarding these, a picture qualitatively comparable to those for CML and CExD is obtained, though with differing weight given to key materials for batteries (e.g., high impacts for cobalt).

When comparing the LCIA methodologies that base their assessment on available stocks (CML, CExD, AAPD, EcoSC), some key materials can be identified that cause the main discrepancies between the different RDP results, above all, tantalum, cadmium and indium. Here, further work needs to be done for a better understanding of the origins of these differences. A detailed study of resource extraction and consumption flows by means of material flow analysis, but also investigations on actually available resources, could help to reduce uncertainty. For the remaining metals, the results vary, but show a comparable overall picture, which is why the findings can at least qualitatively be considered representative.

3.4. Allocation of Resource Depletion to Co-Products

A general problem independent of the different RDP impact assessment methodologies and rather an issue of the ecoinvent database model, is how to deal with mixed ores. Almost all ores contain more than just one metal, and the environmental impacts associated with ore mining and processing are usually allocated to the different metals contained in these ores according to economic aspects [37]. Thus, the depletion of the principal metal is also associated with resource depletion impacts for the co-mined metals. This might also cause a problem of “double-counting” of impacts for a system requiring, e.g., Ni and Co, because the demand for each metal causes separate RDP impacts for the two resources. Up to which point this represents the actual situation can certainly be discussed. It appears strange to see the high contributions of, e.g., cadmium, molybdenum or indium to the total RDP obtained for the LIBs, considering that these materials are not contained in the batteries. On the one hand, resource production and consumption follows market mechanisms, and an increase in mining of one metal will increase the availability of the co-mined materials. This would lead to price adjustments that again trigger changes in consumption, such that the co-products will potentially be absorbed by the market. On the other hand, mining a metal only causes its availability, and not yet its depletion. If the co-mined metal was stored until required this would even be a benefit for future availability of this material. For instance, cadmium or indium are contained in the tailings of zinc mines, and can be recovered from there under favorable economic circumstances. With low market prices, they would be left over in the tailings and thus still be available on the mining site for future recovery. In this sense, the co-extraction of these metals due to zinc mining is not a depletion issue unless other processes require this material and use/dissipate it. Only if part of the indium/the tailings were lost, e.g., to rivers due to erosion or the like, the corresponding depletion also of the secondary metals would have to be accounted to the primary process. Under this paradigm, multi-output mining processes would not use allocation for resource flows, but account only for the target material, since the co-mined materials are not lost or dissipated due to the mining activity, but rather made available. The processes that use/dissipate these materials would account fully for the corresponding RDP.

4. Conclusions

A high heterogeneity can be observed between the results obtained with different methods for assessing the resource depletion potential (RDP) of lithium-ion batteries within LCAs. It seems that all known RDP impact assessment methods have some major drawbacks, which influence the gained results significantly. Thus, no final conclusion can be obtained about which materials are most problematic for current LIBs. Nevertheless, some trends can be pointed out: cobalt and nickel, though weighted very differently, turn out to be critical substances within all methods. The same applies to copper and the (semi-) precious metals required for the battery electronics, above all, gold and silver. The electronic components are also responsible for the demand for tantalum (capacitors required for the BMS), which shows extraordinarily high resource depletion impacts with three of the five methodologies (CExD, CML-rb/CML-er and EcoSc). Hence, the battery management system and electronic parts (also cables) can be identified as one of the key drivers for resource depletion and require special attention when modelling LIB systems. Depending on the research questions to be addressed, it might be helpful to consider both, batteries with and without BMS, in future assessments, thus providing a more detailed picture of their potential resource depletion.

Regarding the battery chemistries, an advantage can be observed on a mass basis (per kg of battery produced) for the LFP-type lithium-ion battery and for the sodium-ion battery, obtained with the majority of the applied LCIA methods. The former can be attributed to the absence of critical materials like cobalt or nickel in the cathode material, the latter to the use of aluminum instead of copper for the anode current collector, which reduces copper demand and associated resource depletion. Eliminating or lowering the use of cobalt, nickel and copper can thus be considered another design goal for developing batteries with minimized resource demand. However, on a capacity basis (per kWh of storage capacity), the differences between the battery chemistries are comparably small,

and the ranking changes with different LCIA methodologies. Thus, no recommendation can be given in this regard, but a high sensitivity to the energy density can be pointed out. Achieving higher energy densities reduces the battery mass required for providing a given storage capacity and, thus, the resource depletion impacts correspondingly.

Future work should also focus on modelling end-of-life pathways for current LIBs. While only a few works are available on this aspect, this is a fundamental issue still associated with high uncertainty. Recycling processes that recover all materials in high quality could help reduce resource depletion significantly. Apart from that, the allocation approach used in the ecoinvent datasets for distributing environmental burdens between co-products might need to be revised for the resource flows. While allocation makes sense for other impact categories, it might not for RDP. Mining of a mineral co-extracts others, but does not necessarily deplete them in the sense of future availability. Considering this aspect would be one step further towards a dissipation-based approach of assessing resource depletion. In general, there is still some research work to be done for the development of a robust resource depletion impact methodology that considers all the mentioned disadvantages of the present methods. This would help to gain more reliable results and support a fair consultation of different stakeholders in the field of technology development.

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Abbreviations

AADP	Anthropogenic stock extended Abiotic Depletion Potential (impact assessment methodology)
BMS	Battery Management System
CExD	Cumulative Exergy Demand (impact assessment methodology)
CML	Name of LCIA methodology (derived from 'Centrum voor Milieukunde, Leiden University')
EcoSc	Ecological Scarcity (impact assessment methodology)
EI99	Eco Indicator 99 (impact assessment methodology)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ILCD	International Reference Life Cycle Data System
LIB	Lithium-Ion Battery
RDP	Resource Depletion Potential
ReCiPe	Name of LCIA methodology
-rb	reserve base (approach for estimating global reserves; CML methodology)
-er	economic reserve (approach for estimating global reserves; CML methodology)
-ar	absolute reserve (approach for estimating global reserves; CML methodology)

Battery chemistries

LFP	Lithium-Iron-Phosphate LiFePO_4 (cathode material)
LTO	Lithium-Titanate $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (anode material)
NCM ³³³	Lithium-Nickel-Cobalt-Manganese-Oxide $\text{LiNi}_{0.33}\text{Co}_{0.33}\text{Mn}_{0.33}\text{O}_2$ (cathode material)
NCM ⁴²⁴	Lithium-Nickel-Cobalt-Manganese-Oxide $\text{LiNi}_{0.4}\text{Co}_{0.2}\text{Mn}_{0.4}\text{O}_2$ (cathode material)
NCA	Lithium-Nickel-Cobalt-Aluminium-Oxide $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ (cathode material)
NMNT	Sodium-Nickel-Manganese-Magnesium-Titanium-Oxide $\text{Na}_{1.1}\text{Ni}_{0.3}\text{Mn}_{0.5}\text{Mg}_{0.05}\text{Ti}_{0.05}\text{O}_2$ (cathode material)
LMO	Lithium-Manganese-Oxide LiMnO_2 (cathode material)

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