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Review

A Review of Life Cycle Assessment Studies of Electric Vehicles with a Focus on Resource Use

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Abstract: Changes in the mobility patterns have evoked concerns about the future availability of certain raw materials necessary to produce alternative drivetrains and related batteries. The goal of this article is to determine if resource use aspects are adequately reflected within life cycle assessment (LCA) case studies of electric vehicles (EV). Overall, 103 LCA studies on electric vehicles from 2009 to 2018 are evaluated regarding their objective, scope, considered impact categories, and assessment methods—with a focus on resource depletion and criticality. The performed analysis shows that only 24 out of 76 EV LCA and 10 out of 27 battery LCA address the issue of resources. The majority of the studies apply one of these methods: CML-IA, ReCiPe, or Eco-Indicator 99. In most studies, EV show higher results for mineral and metal resource depletion than internal combustion engine vehicles (ICEV). The batteries analysis shows that lithium, manganese, copper, and nickel are responsible for the highest burdens. Only few publications approach resource criticality. Although this topic is a serious concern for future mobility, it is currently not comprehensively and consistently considered within LCA studies of electric vehicles. Criticality should be included in the analyses in order to derive results on the potential risks associated with certain resources.

Keywords: life cycle assessment; electromobility; resources; resource depletion; criticality; supply risks

1. Introduction

In recent years, societal and political interest in electric mobility has increased due to rising environmental challenges such as climate change, inner city pollution, and predicted shortage of fossil fuels [1]. A reduction in fossil resource use and environmental impacts is predicted when changing from combustion engines to alternative drivetrain technologies including electric vehicles (EV). Several countries have already set goals for the future share of electric vehicles or launched programs for their market introduction [2]. The European Union for example aims at cutting the vehicles with combustion engines in half by 2030 and phasing them out in cities by 2050 [3]. Sales of electric vehicle are on the rise worldwide, with China and Norway being the main drivers. In the coming years, an enormous increase in sales of electric vehicles is predicted to reach about 4 million in 2020, 18 million in 2025, and 21 million in 2030 [2,4–8].

Concerns about introducing electric vehicles in a mass market are mostly related to an elevated demand of resources, e.g., the use of lithium in lithium ion batteries [9–14]. The growing material consumption by the industry and the need for higher resource efficiency are issues which have been heavily discussed in the last years [15,16]. The replacement of conventional vehicles by EV means a profound change in the resource use patterns worldwide. In particular, the demand for lithium, cobalt, rare earth elements, and graphite, which are essential for battery production, is expected to increase vastly, as shown in Figure 1. It is predicted that the demand for lithium-ion batteries will grow seven times by 2025 and by 11–13 times by 2030 [5,17]. An inadequate supply of these resources might have implications on economic prosperity and employment [18].

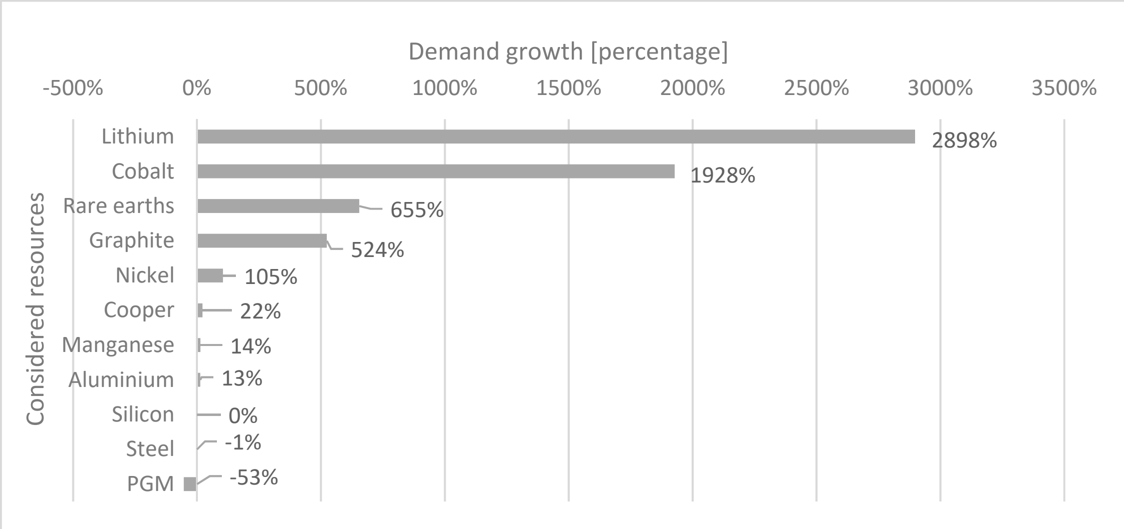

Figure 1. Predicted increase in resource demand in a 100% electric vehicles (EV) world (percentage change compared to today's global production) [19].

Life cycle assessment (LCA) [20,21] is a method that could be used to investigate potential environmental impacts of the resource use of different drivetrain technologies. Over the past decade, many publications have analyzed the environmental impacts of alternative drivetrain technologies compared to conventional vehicles powered by internal combustion engines. Multiple methods to assess resource efficiency of product systems have been developed and integrated into LCA [22].

As shown by Berger et al. (2020) [22] and Sonderegger et al. (2020) [23], for the assessment of resource use several methods exist addressing a variety of aspects including the depletion of resources, future efforts of mining resources, thermodynamic accounting, and supply risks. Depending on the research question, one or more methods could be chosen. For example, to determine the depletion of resources by considering currently existing and developing mines, the abiotic resource depletion (ADP) method [24–26] based on economic reserves is chosen to answer this question.

The present article provides an overview of LCA studies on electric vehicles and the respective batteries published over the last 10 years. It analyzes whether and how the reviewed publications address the impact category "resources". The focus of the publication is on metals and mineral resources. For that, we investigated which impact assessment methods for resource use are applied, as well as the overall conclusions regarding resource use for electromobility. It is also verified if the applied assessment methods are suitable to address the criticality of resources.

2. Methodology

This article analyzed LCA studies on electric vehicles from 2009 to 2018 (included). For this, the databases *ScienceDirect* and *Web of Science* were searched using the following keywords: "LCA" OR "life cycle assessment" AND "electromobility" OR "electric vehicles". From all identified studies, studies were selected which attended following criteria: (a) an LCA of a vehicle or vehicle parts was conducted; (b) results were displayed in impact categories and an interpretation was performed.

The selected studies were examined in a four-step approach (see Figure 2). In the first step, key information of the studies was extracted considering following aspects:

- author(s),
- title of publication,

- date of publication,
- objective of the study,
- functional unit,
- analyzed drivetrain technologies, vehicle parts, and life cycle stages,
- considered impact categories and applied impact assessment methods (see Section 3.1).

In the second step, a refinement of publications with focus on resource use assessment was performed. Special attention was given to studies analyzing the battery of EV, since it is a potential hotspot for the use of critical materials in electric mobility. In the third step, publications considering resource use were investigated regarding their applied impact assessment methods (see Section 3.2). Again, a focus was laid on batteries of EV (see Section 3.3) and whether the studies considered resource depletion or criticality (see Section 3.4). In the last step, overall conclusions on the resource use in the examined case studies were drawn (see Sections 4 and 5).

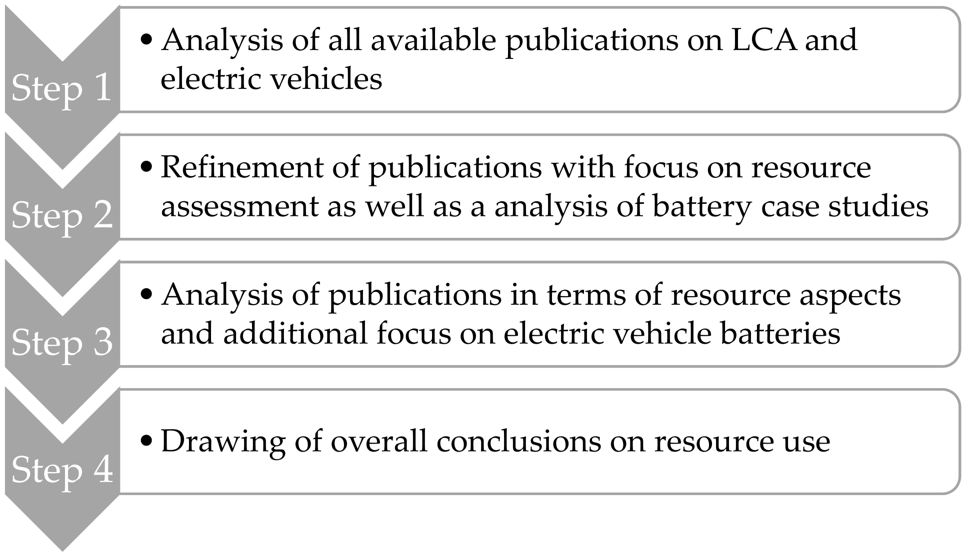

Figure 2. Four-step approach to analyze selected studies.

The term "electric vehicle" (EV) comprises vehicles with different types of engine and may include battery electric vehicles (BEV), which draw all of their power from the electric grid and hybrid electric vehicles (HEV) including plugin hybrid electric vehicles (PHEV), which combine an internal combustion engine with an electric propulsion system. For the purpose of this publication, the term EV will be adopted for all types of passenger electric vehicles.

3. Results

Altogether, 103 publications were analyzed, whereas 76 considered a complete LCA of an electric vehicle (see Figure 3) and 27 studies focused exclusively on battery production. Most papers were published in the years 2015, 2017, and 2018. Overall, an increasing trend of publications was observed, which reflects the growing interest in analyzing electromobility from the life cycle perspective.

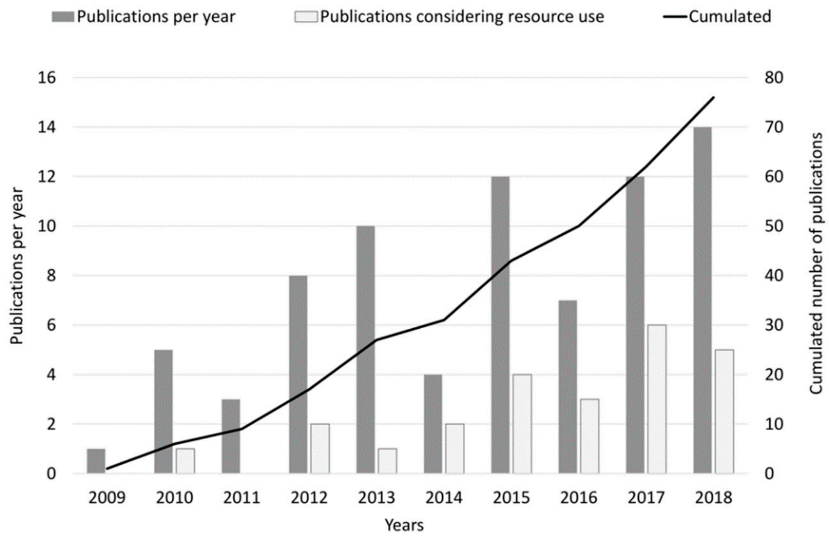

Figure 3. Yearly and cumulated number of publications performing life cycle assessment (LCA) on electromobility as well as number of publications considering resource use.

Most of the examined studies (65) aimed to compare environmental impacts of emerging drivetrain technologies (e.g., battery electric vehicle) with conventional internal combustion engines. The other studies did not perform any comparison, examining only electric vehicles. A total of 45 of the studies investigated the vehicles entire life cycle, i.e., material extraction, vehicle construction, use, and end-of life phase. Four of the overall reviewed studies concentrated solely on the use phase of electric vehicles and partly compared them with the use of conventional technologies. Three other studies evaluated only the manufacturing stage. A total of 13 of the studies investigated the well-to-wheel impacts but did not consider end-of-life.

3.1. Evaluated Impact Categories

In Figure 4, the considered impact categories as well as applied methods are presented. As very different types of impact categories were applied in the examined studies, similar impact categories were aggregated for this review in order to facilitate the interpretation of results. Overall, five impact clusters could be identified: *climate change*, *energy*, *resources*, *damages to air*, *water and land,* and *human health*. The cluster *climate change* contains the categories *global warming potential*, *carbon dioxide emissions,* and *greenhouse gases emissions*. *Energy use* and *cumulative energy demand* were subsumed under the cluster *energy*. Additionally, other formulations in relation to *energy consumption* were summarized under this term (e.g., *primary energy demand*, *energy consumption* etc.). Other frequently used categories like *particulate matter formation*, *ozone layer depletion*, *photochemical oxidation*, *freshwater and marine aquatic ecotoxicity*, *acidification*, *eutrophication*, *terrestrial ecotoxicity,* and *land use change* were aggregated under *damages to air, water, and land*. The category *human health* only covers the impacts from *human toxicity.* The cluster *resources* contains the impact categories *abiotic depletion*, *mineral resources depletion*, *metal depletion*, and *fossil resources depletion*.

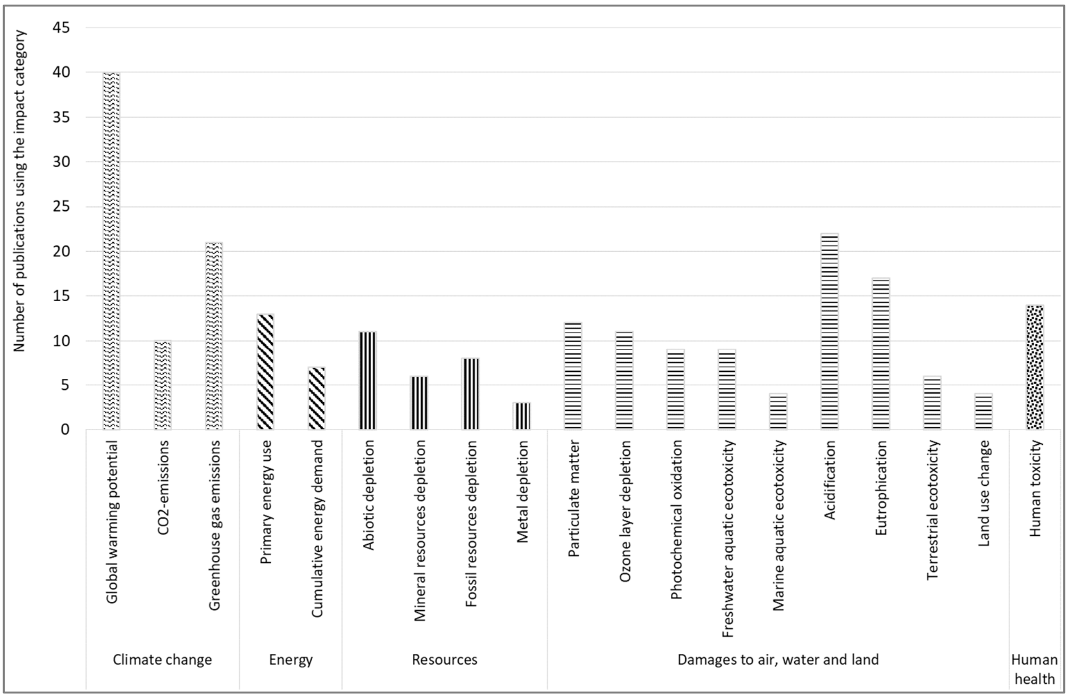

Figure 4. Overview of the impact categories applied in the analyzed publications.

As shown in Figure 4, most studies analyzed a variety of impacts and did not focus much on resource use assessment. The majority of the studies addressed the impact category climate change (also referred to as greenhouse gas emissions, carbon dioxide emissions, and global warming potential). Further, it is apparent that another emphasis was on the impact categories acidification and eutrophication.

3.2. Assessment of Resource Use in Electric Vehicle LCA

In this section, publications considering resource use were analyzed. A total of 25 publications addressed resource use related to electric vehicle production and use stage. Different assessment methods were applied, but some authors did not apply any impact assessment method to assess resources and solely tracked the used resources for the production of an electric vehicle without any further investigation. In step 2, a refinement was done, and 15 publications were selected for further analysis. All selected publications evaluated complete vehicles and provided impact assessment of vehicle manufacturing, operation, and end-of-life (see Table 1).

In seven publications, the ADP method as part of CML-IA (Centrum voor Milieuwetenschappen – Impact Assessment) was applied—with its different versions regarding characterization factors (CFs) [27]. In CML-IA, resource use is evaluated by the indicator abiotic resources depletion (ADP) [28]. Most of the authors that applied CML-IA used ADP in its aggregated form (with $ADP_{elements}$ and ADP_{fossil} being merged). However, the CML-IA authors advised against such a practice and provided separate lists of CFs [27]. When fossil, mineral, and metallic resources were assessed jointly (aggregated ADP), EV achieved better results than ICEV due to higher influence of fossil fuels in the overall life cycle of the vehicles [29–32]. An exception was Yu et al. (2018) [33], where EV performed worse than the ICEV. A separate assessment of $ADP_{elements}$ led to higher impacts of EV if compared to ICEV [34,35].

In three other publications, the ReCiPe method [36] was used, which applies the indicators mineral resource depletion (MDP) and fossil resource depletion (FDP). When ReCiPe was applied, EV performed worse than ICEV in MDP, but better in FDP. Even though EV showed higher MDP impacts than ICEV (threefold for Hawkins et al. (2013) [37] and Helmers et al. (2017) [38]), this result might be even higher, because ReCiPe does not include CFs for lithium (as noted by Hawkins et al. (2013) [37]), and consequently underestimated the battery influence.

Further, the remaining studies applied the EDIP method 2003 [39], the Geopolitical Supply Risk method [40–42], the Eco-Indicator 99 [43] and the ESSENZ method [44,45].

In summary, it could be noted that, especially when the use phase was estimated to be rather short or recycling rates were low, EV performed worse than ICEV [46,47]. This can be explained by a higher demand in metals for EV production [33–35,48]. When impact categories related to fossil resources use were used, most of the publications evaluated EV better than ICEV, since EV have a negligible fossil fuel consumption throughout their lifetime.

Most of the authors underlined that the worse results achieved by EV in the mineral or metal related categories were due to battery manufacturing [33,35]. As shown in Helmers et al. (2017) [38], the battery production of EVs has much larger impacts than the one from ICEV. However, considering the overall impacts from EV, the component "printed wiring boards" in the power train was the component with the highest burdens due to the microelectronics containing (rare) metals such as silver, gold, tin, and lead.

Sensitivity analyses were performed in five of the 15 publications. The identified trend regarding burdens due to resource use was emphasized in all performed sensitivity studies, highlighting the robustness of the results.

Table 1. Summary of the selected LCA that cover resource use assessment.

Author, Year	Title	Functional Unit	Impact Assessment Methods for Resources/Impact Categories	Conclusion of Resource Use Assessment	Results of Sensitivity Analysis with regard to Resource Use
Notter et al. 2010 [29]	Contribution of Li-ion batteries to the environmental impact of electric vehicles	One average kilometer driven by a vehicle with electric drivetrain and Li-ion batteries on the European road network	CML-IA 2002/ADP	EV have a 37% lower burden than ICEV	Sensitivity analysis only carried out related to environmental impacts
Bartolozzi et al. (2013) [30]	Comparison between hydrogen and electric vehicles by life cycle assessment: A case study in Tuscany, Italy	200 km at nominal full load within an urban area	CML-IA 2002/ADP	EV have an 80% lower burden than ICEV	No sensitivity analysis was carried out
Hawkins et al. (2013) [37]	Comparative environmental life cycle assessment of conventional and electric vehicles	1 km driven under European average conditions	ReCiPe/MDP and FDP	MDP: EV has a roughly three times higher burden than ICEV FDP: EV perform between 25% and 30% better than ICEV (average EU mix)	MDP: increase of vehicle life reduces burdens by EV more significantly as for ICEV, but EV still has higher burdens even with highest vehicle lifetime FDP: decrease of energy use for EV and fuel use for ICEV reduces burdens by EV more

					significantly as for EV, therefore emphasizing the better result of EV
Messagie et al. (2014) [46]	A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels	1 km driven under European conditions	Eco-Indicator 99/mineral resource depletion (MRD)	EV have slightly lower (5%–10%) burden than ICEV	No sensitivity analysis was carried out
Girardi et al. (2015) [31]	A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study	Lifetime of the vehicle (150,000 km)	CML-IA 2002/ADP	EV have 40% lower burden than ICEV	Sensitivity analysis only carried out related to environmental impacts
Tagliaferri et al. (2016) [35]	Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach	1 km driven by one vehicle	CML-IA 2002/ADP_{fossil} and $ADP_{elements}$	ADP_{fossil}: EV has lower burden than ICEV (50% less in one scenario and almost two times in another) $ADP_{elements}$ (assumption of "high recycling rate"): EV	ADP_{fossil}: change of electricity in 2030 and 2050 with less fossil and more renewable and nuclear energy as well as more biodiesel fuel, does

				has higher burden than ICEV (almost nine times more in one scenario and three times more than ICEV in another)	not change the lower EV burden $ADP_{elements}$ was not considered in the sensitivity analysis
Henßler et al. (2016) [34]	Resource efficiency assessment—comparing a plug-in hybrid with a conventional combustion engine	Life cycle of one car	ESSENZ method/ADP_{fossil} and $ADP_{elements}$	ADP_{fossil}: EV (when using electricity from hydropower) has lower burden (40%) than ICEV $ADP_{elements}$: EV has higher burden (170%) than ICEV	No sensitivity analysis was carried out
Cellura et al. (2016) [49]	Electric mobility in Sicily: an application to a historical archaeological site	Transportation of one person for 1 km (1 pkm)	ADP applied as recommended by life cycle data system (ILCD) 2011	ADP is on average 500% higher for BEVs than for ICEVs; the highest impact for BEV when it is powered by solar energy (PV) (ca. 1100% higher impacts in comparison to ICEV average)	No sensitivity analysis was carried out
Choma et al. (2017) [32]	Environmental impact assessment of increasing electric vehicles in the Brazilian fleet	Transportation of one person for 1 km (1 pkm)	CML-IA 2002/ADP	EV have lower burden (between one-third and 80%) than ICEV	ADP: different electricity as well as fuel sources are considered, not changing the trend

					that EV has lower burdens than ICEV
Cimprich et al. (2017) [40]	Extension of geopolitical supply risk methodology: characterization model applied to conventional and electric vehicles	Production of one vehicle	GeoPolRisk	EV has higher criticality compared to ICEV; EV has higher ADP potential than ICEV	No sensitivity analysis was carried out
Helmers et al. (2017) [38]	Electric car life cycle assessment based on real-world mileage and the electric conversion scenario	100,000 km driven under European average conditions	ReCiPe/MRD, FDP	MRD: EV has three times higher burden than ICEV FDP: ICEV has three times higher burden than EV	Four different electricity and urban vs. mixed driving conditions were considered, emphasizing the results for MRD (ICEV has lower burdens as EV) and FDP (EV has lower burdens than ICEV)
Van Mierlo (2017) [50]	Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment	1 km driving distance	ReCiPe/MRD, Eco-Indicator 99—Metal depletion	Lower metal depletion scores for lithium iron phosphate-based batteries	No sensitivity analysis was carried out
Souza et al. (2018) [51]	Comparative environmental life cycle assessment of conventional vehicles with different fuel	Vehicle with an occupation of 1.6 persons and a total life traveled distance 160,000 km	CML-IA 2002/ADP_{fossil} and $ADP_{elements}$	$ADP_{elements}$: burdens of EV and ICEV are similar; ADP_{fossil}: EV has ca. 2.5 lower burden than ICEV	Changes in energy supply use for fuels and electricity ADP_{fossil}: emphasizes trend that EV has

	options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil				lower burdens than ICEV, except for ethanol based ICEV, which scores better than the EV $ADP_{elements}$: no changes, since the assumptions for manufacturing phase remained the same
Del Pero et al. (2018) [48]	Life cycle assessment in the automotive sector: a comparative case study of internal combustion engine (ICE) and electric vehicle	Lifetime of the vehicle 150,000 km	ADP applied as recommended by life cycle data system (ILCD) 2011	EV has a higher burden (ca. 32%) than ICEV	No sensitivity analysis was carried out
Yu et al. (2018) [33]	Life cycle environmental impacts and carbon emissions: a case study of electric and gasoline vehicles in China	Life cycle vehicle travelling (250,000 km)	CML-IA 2002/ADP	ICEV has six times lower burden than both analyzed types of EV (with lithium-iron and nickel-based batteries)	Sensitivity analysis only carried out related to environmental impacts

3.3. Assessment of Resource Use in LCA Battery Studies

As the analyses in Section 3.2 showed, impacts due to resource use of electric vehicles were higher compared to ICEV. Helmers et al. (2017) [38] found that mineral depletion is mainly dominated by powertrain and battery production. Further, Messagie et al. (2013) [52] stated that the battery production has a significant influence on the total impact of a battery electric vehicle. Both authors found that the use of mineral resources is a key issue in battery manufacturing, especially for lithium. Raw materials like copper, nickel, cobalt, and graphite were also relevant for electric and hybrid vehicles with rechargeable batteries [53,54]. Further, rare earth elements like neodymium and dysprosium were used in permanent magnets for electric motors. In order to reflect more on this issue, further LCA studies that explicitly concentrate on electric vehicle batteries were analyzed in terms of their methods and findings related to resource use.

Out of the 27 additionally identified studies, 13 considered the total life cycle of the battery, i.e., battery production, use phase, and end-of-life treatment. Four studies focused on the end-of-life phase. Ten of the 13 studies analyzing the whole life cycle addressed resource use. These studies mainly evaluated lithium-ion batteries with different cathode materials. Figure 5 depicts the considered impact categories in the reviewed battery studies. The clusters (i.e., climate change, energy, resources, damages to air, water and land, and human health) and associated impact assessment methods are in accordance with Figure 4.

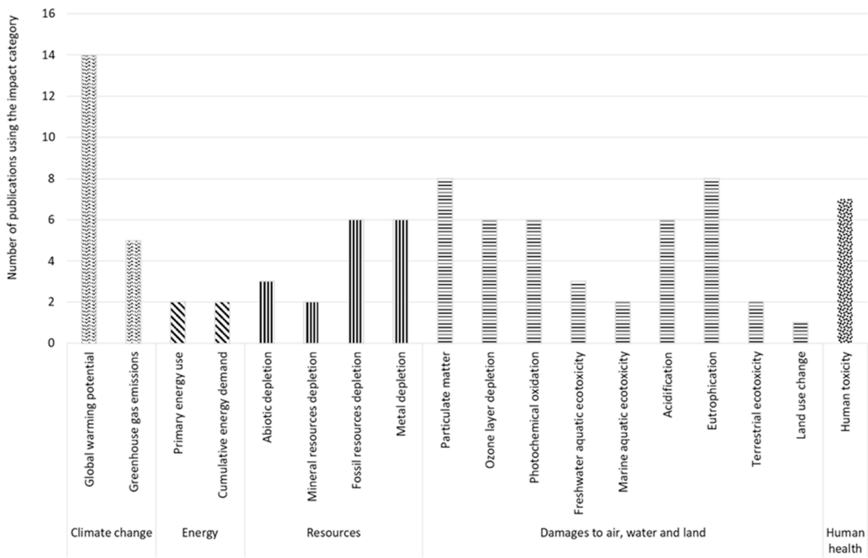

Figure 5. Evaluated impact categories within the reviewed battery studies.

Table 2 gives an overview of the applied functional units, impact assessment methods, a short summary of their findings regarding resource use, as well as information on findings from sensitivity analysis for the 10 studies. Five of the studies use ReCiPe [55] and four apply CML-IA to assess impacts of resource use. One of the studies compared the application of six different impact assessment methods to assess resource use [56]. Besides CML-IA, ReCiPe, and Eco-Indicator 99, the anthropogenic stock extended abiotic depletion potential (AADP) [57,58], Cumulative Exergy Demand (CExD) [59], and the Ecological Scarcity Method (EcoSc) [60] were applied as well and besides ReCiPe and Eco-Indicator 99, the other methods led to high results due to use of tantalum, cobalt, nickel, cadmium, and lithium.

Table 2. Analysis of the selected battery LCA that cover resource use assessment.

Publication, Year	Assessed Battery Chemistries	Functional Unit	Impact Assessment Methods for Resources/Impact Categories	Conclusion of Resource Use Assessment	Results of Sensitivity Analysis with regard to Resource Use
Majeau-Bettez et al. (2011) [61]	Lithium-ion and nickel metal hydride (NiMH); NCM; iron phosphate lithium-ion (LFP)	50 MJ accumulated by the battery and delivered to the powertrain (roughly driving 100 km)	ReCiPe 2008/FDP and MDP	Highest MDP of NiMH batteries because of electrode materials nickel and lanthanum; NCM have higher impacts than LFP due to use of nickel, cobalt, and partly from copper; mining and metallurgy activities for nickel production are responsible for 80% of MDP. Electricity consumed (European electricity mix) during use phase contributes to more than 40% of FDP; highest burdens found for NiMH	Sensitivity analysis only carried out related to environmental impacts
McManus et al. (2012) [62]	Lead acid battery, nickel cadmium; nickel metal hydride; lithium-ion; sodium sulphur battery	100 kg (of battery)	ReCiPe 2008/FDP and MDP	Highest burdens of lithium-ion batteries in FDP and MDP due to metal depletion from ferrite production; lead acid batteries have the lowest impacts	No sensitivity analysis was carried out

Faria et al. (2014) [63]	Lithium manganese oxide battery (LMO)	200,000 vehicle km (service life of the vehicle)	CML-IA 2001/ADP elements	Cathode of lithium-ion battery contributes by 28% to ADP elements due to lithium or manganese use	No sensitivity analysis was carried out
Ahmadi et al. (2017) [64]	Iron phosphate lithium-ion battery	Energy provided over the total battery life cycle in kWh	ReCiPe 2008/FDP and MDP	Trade-offs by extending the service life of battery pack: MDP increases due to higher demand for virgin materials but less fossil fuel use (FDP)	Sensitivity analysis considering battery degradation: only minor effect on metal depletion; greater influence on fossil depletion. The higher the degradation rate the lower the energy efficiency, which increases energy use
Messagie et al. (2015) [65]	LMO; lithium iron phosphate (LFP)	1 kWh of energy stored in the battery	ReCiPe 2008/MDP	Higher MDP impacts for LMO batteries due to manganese and copper use; benefits due to material recycling	No sensitivity analysis was carried out
Sanfelix et al. (2015) [66]	Lithium manganese oxide cells; hybrid systems from lithium iron phosphate cells prolong the lifetime	1 km driven under European average conditions	CML-IA 2002/ADP elements	The credit from recycling of a hybrid energy storage system offsets ADP impacts from manufacturing and use phase; metal use and the necessary mining operations for a hybrid energy storage system cause most of	No sensitivity analysis was carried out

				the resource depletion impacts	
Peters et al. (2016) [56]	Sodium ion; LFP; LFP-with lithium-titanate anode (LFP-LTO); LMO; NCA; NCM	1 kg and 1 kWh	ReCiPe 2008, Eco-Indicator 99/minerals, CML-IA 2002/ADP (different reserve bases); AADP, CexD, EcoSc	Worst results of NCM in CML-IA, AADP, EcoSC, and CexD but not in Eco-Indicator 99 and ReCiPe (for functional unit in kWh); best results of LFP with almost all methods besides CML-IA and sodium-ion batteries (for functional unit in kg) if CML-IA is applied Most of the methods show impacts from copper use; in CML-IA, AADP, EcoSC, CexD, highest impacts from use of tantalum, cobalt, nickel, cadmium, partly to lithium	No sensitivity analysis was carried out
Zackrison et al. (2016) [67]	High-capacity lithium-air batteries	Vehicle kilometer	CML-IA 2002/ADP	Highest burdens due to production phase (89% copper, 5% lithium); recycling avoids burdens from depletion	Sensitivity analysis only carried out related to environmental impacts
Van Mierlo et al. (2017) [50]	LMO, LFP; sodium-nickel chloride; lead	1 kWh	ReCiPe/MDP	Much higher MDP for LMO batteries than for LFP batteries because	No sensitivity analysis was carried out

	acid nickel cadmium; nickel metal hybrid			of high manufacturing burdens. Which materials are responsible was not analyzed. Separate discussion of lithium availability. Materials recycling can have significant benefits. proper material recycling is needed to prevent lithium shortage in EV industry	
Bobba et al. (2018) [68]	LMO; nickel-manganese-cobalt (NMC)	Average yearly energy balance of the system in which the battery stores energy	CML-IA 2002/ADP	The use of repurposed batteries from mobility application reduce ADP impacts; no detailed analysis of the contribution of certain materials	Changing the allocation factors (>0) for the manufacturing/end of life (EoL) of repurposed EV batteries, benefits from battery reuse largely diminish—especially for impact categories dominated by manufacturing/EoL (i.e., ADP); the higher the residual capacity the higher the level of benefit especially for ADP

Studies applying ReCiPe found high impacts for nickel containing battery types and lithium-ion batteries with iron electrodes [61,62,64]. However, results might be influenced by missing CFs (see Section 4). Some authors therefore discussed lithium availability separately [62,65]. However, not only lithium but also other metals like manganese, cobalt, nickel, and copper showed a high impact in the resource use impact categories [56,65]. Generally, extraction and processing of metals had the largest contributions.

The evaluated studies mostly used a functional unit based on the battery capacity, represented by an energy unit (MJ or kWh) to reflect the energy that the vehicle receives from the battery [56,61,64,65]. Some studies used distance as a unit to assess the impacts over the entire life cycle of the battery or over 1 km of travel [63,66,67]. One study based the assessment on the battery weight [62], whereas another one looked on an extended life cycle of batteries from mobility application as stationary storage systems [68]. Peters and Weil (2016) [56] pointed out that the definition of the functional unit indirectly influences the impact assessment results. The authors showed that lithium-nickel-cobalt-manganese-oxide (NCM) and lithium-nickel-cobalt-aluminum-oxide (NCA) batteries performed worse than other batteries when a mass based functional unit was chosen. Since those battery types have higher energy densities, the results would be different if an energy based functional unit was chosen. Using a mass based functional unit, lithium-iron-phosphate (LFP) and sodium-ion batteries performed best [56]. Therefore, recommendations for battery types should not be given when using a mass based functional unit.

Several studies concluded that battery recycling could improve resource use impacts. According to Bobba et al. (2018) [68], a reduction of impacts would occur even if the battery capacity is lower in the second life cycle. If the battery is reused, its service life is expanded and the impacts related to a performance oriented functional unit decrease [50,67]. In addition to this general finding of positive effects of service life expansion, other studies also discussed its negative effects [64,66]. When expanding a battery's service life, the resources were only available in an alternate point of time and primary materials had to be used instead, which leads to higher impacts in the category resource depletion.

3.4. *Criticality Assessment*

As in this section criticality assessment will be discussed, the term criticality is explained in more detail. As stated by Cimprich et al. (2019) [40], the concept of criticality was addressed in terms of risks of supply disruptions (or supply risks). Potential impacts of supply disruption—referred to as vulnerability—were also included in most criticality assessments [69,70]. For the analysis performed in this work, the term criticality was applied to methods addressing only supply disruptions as well as to methods addressing supply disruptions as well as vulnerability. Further, also qualitative approaches discussing the availability of certain raw materials were considered.

3.4.1. Assessment of Criticality in Electric Vehicle LCA

The analyzed studies showed that the impacts of resource use shift from the use phase to the production phase when comparing ICEV and BEV [35,38,46,51]. Three out of 14 studies (as shown in Table 1) had some kind of criticality assessment [29,50,51]. Two approached the criticality of materials for electric vehicles by applying new methods (ESSENZ and geopolitical supply risk methodology) to assess criticality in product systems [34,40].

Amongst others, Nordelöf et al. (2014) [71] stated that electric vehicles will more likely face supply risks due to the use of critical raw materials in the production. When investigating the Li_2CO_3 battery, Notter et al. (2010) [29] analyzed the very low lithium criticality in comparison to other components, such as aluminum and copper. According to the authors, these results were valid as long as Li_2CO_3 is produced from brines and not extracted from the Earth's crust, where it is considered as being geochemically scarce. Souza et al. (2018) [51] also pointed out that lithium has a low occurrence in the Earth's crust and the applied impact assessment methods are not adequate to reflect this fact.

Further, Souza et al. (2018) [51] mentioned the possible limitations of cobalt reserves; however, this issue was not further developed in the study. Criticality aspects due to copper in filament and cable production required for electricity production were addressed, however, also not deeply discussed.

Tagliaferri et al. (2016) [35] addressed in more detail the end-of-life of electric vehicle batteries. The authors identified the valuable outputs contained in the slag of batteries such as nickel, cobalt, and manganese and their possible recovery rates. Increasing battery recycling rates could prevent resource scarcity of certain materials and was also mentioned by other authors [33,46] as an essential path to secure future resource supply. However, the benefit of metal recycling (and therefore reduced scarcity of certain metals) was opposed by the high energy requirement for recovery. Nevertheless, Souza et al. (2018) [51] noticed that due to rising raw material costs and legislations (e.g., EU Batteries Directive—2006/66/EC [72]), the recycling of Li-ion batteries could become increasingly attractive also from an economic point of view.

Van Mierlo et al. (2017) [50] highlighted data uncertainties in estimating future demand and supply of lithium. Lithium reserves worldwide are very uncertain, ranging from 4.6 to 39.4 Mt. The authors also noticed that even though lithium reserves and production occurred in several countries, its long-term use for batteries would only be possible with recycling.

Henßler et al. (2016) [34] applied the ESSENZ method considering 11 socioeconomic categories (for example, political stability and trade barriers of supplier countries, price fluctuation of resources) to assess the criticality of resource use for electric cars. The categories "demand growth" and "primary material use" were dominated by the use of lithium in the EV. Hotspots such as platinum, palladium magnesium, lithium, rare earth elements, and tantalum were also identified. It should be noted, however, that this socioeconomic assessment was conducted alongside the LCA and was not a part of the LCA as such.

Cimprich et al. (2017) [40] applied the geopolitical supply risk methodology to compare ICEV and EV. The authors stated that the resources required for EV production had a significantly higher supply risk, showing a higher depletion potential than ICEV. This analysis was also an additional investigation step beyond an LCA study.

The increasing resource demand (and the related consequences of it) as pointed out in Figure 1 for cobalt, nickel, copper, rare earth elements, and graphite was not explicitly covered by any of the analyzed publications. For the end-of-life modelling, most of the authors recommended a high recycling rate in order to achieve better environmental results [33,46], but without investigating the possible scarcity of some of the resources. Finally, the eventually poor mining conditions and related social aspects (e.g., such as child labor in mines) in the supplier countries were not approached in any of the analyzed studies.

3.4.2. Material Availability and Criticality Assessment in Battery Studies

Future material use for energy storage devices will most likely rise due to increasing demand for electric vehicles if current legislations are implemented and emission thresholds come into force [73,74]. If EV dominate the vehicle fleet, lithium demand will increase, since currently lithium-ion batteries are considered to be the most suitable technology due to their energy-to-weight ratio [74].

Peters and Weil (2016) [56] concluded that higher energy densities of battery components reduces battery mass and therefore resource depletion potential. Speirs (2014) [75] found that the future demand cannot be met by current mining rates. As recycling can reduce resource depletion and therefore criticality, it is essential that lithium batteries are recycled [76]. It was predicted that from 2050 onwards, recycled lithium will dominate most of the global lithium supply [50]. Mohr et al. (2012) [77] estimated the ultimately recoverable resources of lithium within the currently known deposits as approximately 23.6 Mt. Following their calculations, there will be a sufficient supply of lithium for battery vehicles in the future. Based on the analysis of Olivetti et al. (2017) [76], the material demand for lithium-ion batteries will likely be met. Rather, they saw potential availability risks for electrode materials, such as cobalt, due to the geographical concentration of mining, which takes place in the Democratic Republic of Congo with most refining facilities located in China. A rapid adoption of electric vehicles therefore might jeopardize a stable supply of materials for production facilities.

Blagoeva et al. (2016) [54] showed that mainly the demand for graphite and lithium will significantly increase by 2030. Nevertheless, due to e.g., adoption of recycling and substitution, the EU might be more resilient to supply bottlenecks. The biggest obstacles would be the timely establishment of lithium production facilities demanded by the automotive industry [54]. Gruber et al. (2011) [78] analyzed 103 known lithium deposits worldwide considering their stocks, location, and geopolitical supply risk. They investigated if the supply of lithium would cover the global demand for electrification of the automobile sector by 2100. Contrary to Blagoeva et al. (2016) [54], they have not found any constraints due to lithium availability even for a high demand scenario.

Next to lithium, also other materials relevant for battery manufacturing were identified as critical. For example, Peters and Weil (2016) [56] identified hotspots in resource depletion for different battery chemistries. Battery chemistries that do not rely on cobalt, nickel, or copper are considered as advantageous because the reduction of these materials can minimize overall resource criticality.

Ziemann et al. (2013) [14] focused on the resource supply for vehicle batteries. Foremost cathode materials like lithium, manganese, and cobalt were identified as essential for electric vehicle batteries. The authors observed that there has been little attention on manganese availability so far, because currently manganese consumption for batteries is marginal. In total 17 Mt of manganese have been mined as manganese ore in 2017 [79]. About 94% of the mined ore is converted into alloys that are used in steel production [14]. However, the demand for manganese could increase to 0.024 Mt for EV batteries. Currently, no recycling or recovery paths exist for this metal. Eventually slag from steel recycling might be used as manganese source, leading to a possible dependency of manganese supply on steel processing.

Bailey et al. (2017) [80] showed that the criticality of rare earth elements for permanent magnets in electric vehicles was higher than for batteries. A constant material supply largely depends on improved recovery and recycling methods. Gemechu et al. (2017) [42] found higher depletion and supply risks for other materials than lithium, showing that the geopolitical risk indicator is dominated by neodymium and magnesium.

In the study of Grandell et al. (2016) [81] the potential future demand of 14 critical metals was estimated (global reserves and resources) by modelling their need for clean energy technologies—considering also batteries and electric vehicles. Especially, rare earth metals for permanent magnets in electric motors and battery electrodes were analyzed. The results were presented for the entire portfolio of future green technologies. For this reason, no precise results on the criticality of the metal supply for the electric car production could be derived from the study. However, the authors pointed out that silver supply might be a bottleneck, because it is required both for photovoltaic applications and for electronic components in electric vehicles. Further, the authors highlighted indium as probably problematic because it is also needed in EV electronics and in solar energy technologies.

Helbig et al. (2018) [11] evaluated the supply risk associated with element use in six different lithium-ion battery types. The highest risk values were obtained for lithium and cobalt-based batteries, since the main materials (lithium and cobalt) showed high supply risk values, while aluminum had the lowest values. Lithium-iron-phosphate based batteries with titanium-based anodes have shown the lowest supply risk scores. The authors advised focusing research on reducing Li-material intensity and to avoid cobalt-dependent battery technologies.

4. General Findings and Discussion

The number of LCA studies addressing electric vehicles has been increasing over the years. In the beginning, most of the authors focused on evaluating solely the impacts related to climate change. However, over time, resource use has also been investigated more intensively.

It is not easy to summarize the findings of the evaluated studies. This is partly due to the different objectives and scope of the studies, but also to the use of diverse impact assessment methods. The most common methods for resource use assessment were CML-IA [24,26] and ReCiPe [55] in its different versions. Most of the authors that applied impact categories related to mineral or metal resources depletion identified lower impacts for ICEV compared to EV. By applying aggregated impact categories (which assess jointly fossil, metal, and mineral use), EV tend to perform better, but exceptions were also found [48,49]. In general, the selection of the impact assessment method influenced the result and decreased the comparability of results, since also the amount of considered CFs may differ between the methods [82].

For example, Eco-Indicator 99 [43] and ReCiPe [55] cover a lower number of minerals than CML-IA [26] and therefore do not provide CFs for lithium, cobalt (Eco-Indicator 99), and rare earth elements, including lanthanum. Thus, it can be assumed that these methods significantly underestimated resource depletion results, explaining the aforementioned lower differences in the total impacts between ICEV and EV. Not all authors specified the baseline year of the applied method, which also makes a comparison difficult because the CFs of certain methods, e.g., CML-IA, are updated regularly [83]. However, it is challenging to elaborate on the real influence of the respective methodological choice, given that the studies vary greatly in terms of functional unit, system boundaries, or deployed databases.

A further weakness of most of the reviewed studies is the lack of original and current data. Most of the studies relied on original data from 2007 [29,46], 2010 [37], and 2011 [33]. Only one of the studies based its assessment on recently (2016/2017) collected data [48]. When evaluating the results of vehicle comparisons based on data from the early 2000s, it should be kept in mind that the production processes, especially for EV, have evolved since then. This may not be reflected in the used datasets. More recent studies already provide updated inventory, including primary industry data [84].

For the battery LCA, the most applied assessment methods were ReCiPe and CML-IA. While for the assessment of the entire vehicle the functional unit was usually the total travelling distance during its lifetime, for the LCA on batteries diverse functional units have been chosen, e.g., battery service life, battery mass, and energy units.

The impacts of mineral resource depletion of nickel-based batteries compared to lithium-ion batteries were higher when ReCiPe was applied and a functional unit in MJ was chosen [61]. When a mass-related functional unit was adopted, the opposite results occurred. This corroborates the assumption from Peters and Weil (2016) [56], who tested different functional units using same data and achieved contrary results. They showed that ADP values calculated by considering the economic reserve and the technical exploitable resource produced similar results, but to a large extent differing from the results calculated by using the ultimate reserve as a basis.

Only a few LCA case studies have explored criticality assessment. When reviewing studies in terms of criticality, it is noticeable that most concerns focused on the future availability of lithium. There is however no consensus if lithium is really a critical element, since there are uncertainties about the extension of its reserves worldwide. In the studies focusing on batteries, cobalt, manganese, graphite, nickel, and rare earth elements were examined in more detail. Especially cobalt was perceived as being problematic due to the high concentration of its reserves and the strongly increasing demand. Additionally, in a further study investigating the historical development of demand for various metals, it was found that cobalt is a very critical factor for the future development of the supply with lithium-ion batteries [85]. Interestingly, the criticality of cobalt was not addressed any deeper, even though it was a hotspot in some of the LCA results and its global demand is expected to increase. Finally, most of the authors agreed on the importance of promoting metal recycling.

Essentially, the applied methods for resource use assessment were more related to resource depletion than to criticality. This is also closely related to the original purpose of LCA—to assess environmental impacts related to a functional unit. On its turn, criticality assessment is a method to assess social and economic impacts of resource availability on a broader scale. Within the framework of the methods CML-IA 2002 (ADP) and EI99 (Mineral Resources), the assessment of resource use is carried out based on geophysical reference values. ReCiPe (mineral depletion), using surplus costs of extraction as a basis of assessment, or ADP, that includes also the anthropogenic stock of resources and Ecological Scarcity Method [60] that is using legislative thresholds as basis, are closer to criticality assessment than the other methods.

Thus, the application of presently available resource use assessment methods for LCA of EV and batteries can provide a first point of reference, but do not reflect the complex relationship between resource availability and supply like criticality assessment does.

5. Conclusion

The use of metal and mineral resources due to the switch from ICEV to EV has not been explored adequately in the current LCA studies. Out of 103 identified LCA studies focusing on EV, only 25 have assessed a resource-related impact category, whereas all of the studies took climate change into account. Among the LCA studies focusing on batteries, only 10 out of 27 analyzed resource use.

The applied methods to determine resource use impacts were predominately CML-IA ($ADP_{elements}$; with its different versions regarding the CFs), ReCiPe (mineral depletion), and Eco-Indicator 99 (mineral resources). Next to methodological variances, also different quantities of CFs for resource use assessment are available in each of existing methods, leading to an incomplete assessment of key materials relevant for electric vehicles and batteries. Criticality of resources was only addressed in 10 studies.

Future LCA studies should properly choose a suitable impact assessment method based on the chosen problem statement (see guidance of Sonderegger et al. (2020) [23] and Berger et al. (2020) [22]) also bearing in mind that not all methods contain CFs for all assessed elements. Further, the importance of criticality assessment into LCA studies to achieve additional results and identify further hotspots is underlined.

Given the overall trend towards EV, it is important to further close the gap of more comprehensive and consistent assessments of their associated resource needs. Without such assessments and proper eco-design actions derived from them, EV might not be the ultimate solution for sustainable mobility.

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