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Review

Lightweighting electric vehicles: Scoping review of life cycle assessments

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ABSTRACT

In this article, we discuss our comprehensive scoping review of the existing literature on “lightweighting” of electric vehicles from a life cycle assessment perspective. Lightweighting – a concept also applied to internal combustion vehicles – aims to improve the energy efficiency of the vehicle by reducing vehicle mass. Lightweighting is especially important for electric vehicles, which, due to their large battery packs, tend to be heavier than their internal combustion counterparts. We conducted two systematic literature searches, across several research databases (Scopus, Web of Science, SAE Mobilus, and Google Scholar), yielding a total of 40 documents. Our analysis of this literature indicates that, from a life cycle assessment perspective, electric vehicle lightweighting has been considered primarily with respect to comparatively smaller vehicles (*e.g.*, passenger cars as opposed to light trucks and heavier commercial vehicles), and for vehicle components shared with internal combustion vehicles (*e.g.*, closures, body-in-white, and suspension components). Ultimately, we do not find a single life cycle assessment study of electric vehicle lightweighting that evaluates a comprehensive set of environmental impact categories, for a whole vehicle, over the whole vehicle life cycle (*i.e.*, from production through end-of-life). We recommend that further research on lightweighting consider the characteristics of electric vehicles while better evaluating environmental impacts and resource use (*e.g.*, regarding critical raw materials supply), considering trade-offs and co-benefits. For example, we highlight opportunities like reducing vehicle and battery size, although these valuable strategies need to be accompanied by changes in consumer and societal behaviour.

1. Introduction

Electric vehicles (EVs), including battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs), are a pivotal component of the transition to a low-carbon economy. Around the world, conventional internal combustion engine vehicles (ICEVs) are being phased out. The EU has proposed that all new light-duty vehicles sold from 2035 be required to be “zero-emission” (European Parliament, 2022). The UK is phasing out light-duty ICEVs by 2030, and requiring all heavy goods vehicles (HGVs) sold to be zero-emission by 2040 (United Kingdom, 2021). In China, 50% of all new vehicles sold from 2035 will need to be “new energy” vehicles – either EVs or fuel cell vehicles (Nikkei Asia, 2020). The USA is targeting 50% of all new light-duty vehicles to be zero-emission by 2030 (The White House, 2021). Similar to the EU, Canada is requiring all new light-duty vehicles to be zero-emission by 2035 (Transport Canada, 2021). It should be noted that these requirements apply only to *new* vehicles; with roughly 60–80 million new light-duty vehicles sold globally each year. At that rate, replacing the entire global fleet of over 1.2 billion light-duty vehicles (Voelcker, 2014), assuming 100% new zero-emission vehicles starting today, would take about 15–20 years. Nonetheless, the future of road-based transportation is evidently electric.

Although the electrification of the transportation sector may be well-intentioned, over two decades of collective experience with life cycle assessment (LCA) – an internationally standardized methodological framework for systematically evaluating the environmental impacts of goods and services (ISO, 2006a, 2006b) – warns of “problem shifting.” Problem shifting occurs when improvements in one respect are problematic in other respects. Previous LCA studies of EVs – in comparison to ICEVs – suggest that while EVs substantially reduce air pollutant and greenhouse gas (GHG) emissions from vehicle operation (especially with a low-carbon electricity supply mix for vehicle charging), the production of EVs (particularly their electric powertrains and high-voltage battery packs) may increase emissions associated with eutrophication and ecological toxicity (Gan et al., 2023; Hawkins et al., 2013). Moreover,

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EVs are expected to increase reliance on “critical raw materials” (CRMs) like rare earth elements, lithium, nickel, and cobalt (Bhuwalka et al., 2021; Cimprich et al., 2017, 2019; Gemechu et al., 2017; Hache et al., 2019; Jones et al., 2020; Valero et al., 2018). Along with significant supply risks, CRMs can also be associated with severe human rights violations (*e.g.*, as with cobalt, which is widely used in lithium-ion batteries for EVs (Church and Crawford, 2020; Huber and Steininger, 2022; Prause and Dietz, 2022)).

One way to mitigate these trade-offs, while maximizing the energy efficiency of EVs (and ICEVs), is to reduce vehicle mass – *i.e.*, through “lightweighting” strategies. Lightweighting of some vehicle components, such as the body-in-white (BIW), can also enable further lightweighting of other components, *e.g.*, by downsizing powertrains, battery packs, braking and suspension systems; this is known as secondary mass reduction (Burd et al., 2021; Egede, 2017; Kim et al., 2011; Lewis et al., 2014; Lewis et al., 2019; Luk et al., 2017; Milovanoff et al., 2019; Monteiro et al., 2022; Raugei et al., 2015). Assuming the functional performance of the vehicle is maintained (*e.g.*, with respect to driving characteristics, passenger and luggage accommodations, and crashworthiness), lightweighting can be considered a *material efficiency* strategy – that is, a way of delivering comparable performance with less material, and ultimately lower environmental impacts from the production of that material (Wolfram et al., 2021). Lightweighting is especially important for EVs, which, given their large battery packs, tend to be significantly heavier than comparable ICEVs (Proskow, 2023). However, lightweighting can also result in problem-shifting, as “lightweight” materials like aluminum and magnesium alloys, and carbon fibre composites, may have higher environmental impacts associated with their production compared to the materials (typically steel) they replace (Delogu et al., 2017; Lewis et al., 2019; Wolfram et al., 2021; Zanchi et al., 2016).

In this article, we conduct a comprehensive scoping review of the existing literature on lightweighting of EVs from an LCA perspective. In section 2, we explain our scoping review methodology, including the research databases searched, the search phrases used, the inclusion and exclusion criteria, and the content analysis of the literature. In section 3, we outline and briefly discuss the results of our analysis. Further discussion, including a reflection on the significance of our results, a consideration of the limitations of our review, and an outlook on future research directions, follows in section 4. We conclude in section 5 by summarizing our high-level observations from our scoping review.

2. Scoping review methodology

We use the term *scoping review*, as opposed to systematic review, as the former is a more accurate characterization of our work in this article. A scoping review is like a systematic review in that it follows a systematic protocol for collecting and analyzing relevant literature (albeit one that may be more iterative and flexible than in a systematic review), but the purpose is different. Whereas a typical systematic review aims to synthesize and evaluate the state of evidence on a specific question(s) – *e.g.*, “To assess the effects of [intervention or comparison] for [health problem] in [types of people, disease or problem and setting if specified]” (Thomas et al., 2023) – a scoping review is broader and more exploratory, aimed at “mapping” bodies of literature and highlighting knowledge gaps to be addressed in future research (Peters et al., 2015). This is precisely our aim with respect to LCA of EV lightweighting.

In an iterative scoping review process, as illustrated in Fig. 1 and explained in the following paragraphs, we analyzed a total of 40 documents collected through two systematic literature searches.

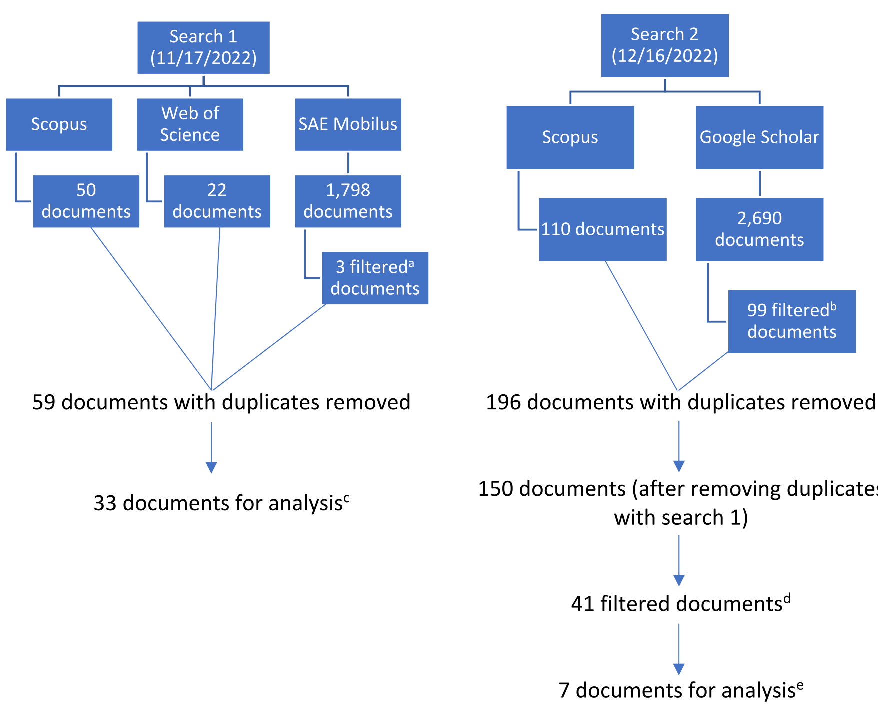

Fig. 1. Literature search process

[a]Limited to: (1) documents published from 1996 onwards (*i.e.*, corresponding to the development of the first international standard on LCA (ISO, 1997)), (2) documents with the terms “electric vehicle” or “hybrid vehicle” in the abstract, (3) documents with the words “weight*” or “mass” in the abstract, and (4) documents with the terms “life cycle assessment” or “life cycle analysis” in the abstract.

[b]Limited to first 10 pages, sorted by relevance.

[c]One document screened out for being published before 1996. 18 documents screened out after reading the abstract and main text. 7 documents not available through the lead authors’ institutional library.

[d]Limited to documents published in the last 10 years, with the terms “weight*” or “mass” in the abstract.

[e]28 documents screened out after reading the abstract and main text. 6 documents not available through the lead authors’ institutional repository.

We began using the following search string in two widely used academic research databases – Scopus and Web of Science (WoS) – and in the Society of Automotive Engineers (SAE) Mobilus database: ("electric vehicle" OR EV OR "hybrid vehicle") AND (lightweight* OR "weight reduction" OR "mass reduction") AND ("life cycle assessment" OR "life cycle analysis" OR LCA). This search string essentially combines keywords representing EVs (including HEVs and PHEVs, but not fuel cell vehicles), lightweighting, and LCA (noting that the term "life cycle analysis," while technically incorrect, is frequently used among non-LCA-experts). This search, conducted on November 17, 2022, yielded 50 documents in Scopus, 22 in WoS, and 1798 in SAE Mobilus (using the filter "sector, automotive").

For the 1798 documents from SAE Mobilus, we applied a series of additional filters limiting the results to: (1) documents published from 1996 onwards (*i.e.*, corresponding to the development of the first international standard on LCA (ISO, 1997)), (2) documents with the terms "electric vehicle" or "hybrid vehicle" in the abstract, (3) documents with the words "weight*" or "mass" in the abstract, and (4) documents with the terms "life cycle assessment" or "life cycle analysis" in the abstract. Together, these filters reduced the initial 1798 documents to 3 relevant documents. This extraordinary narrowing of the search results can be explained by how the SAE Mobilus database interprets the search string; we found that it looks for the *character strings*, as opposed to the words (*e.g.*, the words "every" and "several" contain the character string "ev," and the term "oilcanning" contains the character string "lca").

Removing duplicates across the search results from the three databases yielded a list of 59 documents for review, from which one document was screened out for being published before 1996. A further 18 documents were screened out after reading the abstract and main text (*e.g.*, one article concerned lightweighting of building materials, one was focused on the aviation industry, and several articles did not substantively address lightweighting). Another 7 documents were not available through the lead authors' institutional library, though most of these are conference proceedings, and according to the Scopus database (as of February 1, 2023) they have been cited, on average, less than once per year.

To further survey the relevant literature, we conducted a second search on December 16, 2022. For this search, we included additional keywords representing various "lightweight" materials (*e.g.*, aluminum and magnesium alloys and carbon fibre reinforced polymers) identified in the documents obtained from the first search. We also removed the acronyms for "electric vehicle" and "life cycle assessment," as we expect relevant literature to use the full terms. Our resulting search string was: ("electric vehicle" OR "hybrid vehicle") AND (lightweight* OR "weight reduction" OR "mass reduction" OR steel OR alumin* OR magnesium OR polymer OR "carbon fiber" OR "carbon fibre" OR composite) AND ("life cycle assessment" OR "life cycle analysis"). We entered this search string in Scopus and Google Scholar, yielding 110 and 2690 documents respectively. In Google Scholar, we took the search results from the first 10 pages, sorted by relevance.

Removing duplicates between Scopus and Google Scholar produced a list of 196 documents, which we reduced to 150 by removing duplicates of documents already found in our first search. We further shortened the list to 41 documents for analysis by applying a date cut-off (*i.e.*, including only documents published in the last 10 years) and limiting it to documents with the terms "weight*" or "mass" in the abstract. Notably, the date cut-off for this search (*i.e.*, documents published within the last 10 years) differs from that applied to our first search (*i.e.*, documents published from 1996 onwards). As part of our iterative scoping review process, we realized, after screening the results of the first search, that a 10-year cut-off – roughly corresponding to the first generation of mainstream EVs like the Nissan Leaf, Chevrolet Volt, and Tesla Model S – is reasonable. Notably, many newer EVs have subsequently been introduced, including the Tesla Model 3 (and Model Y, which has recently been redesigned with extensive use of structural aluminum castings), Ford Mustang Mach-E, and a redesigned Nissan Leaf. Documents over 10 years old would be too outdated to reflect the current state of the art – which is ultimately what our review seeks to evaluate. Of the 41 documents collected through our second literature search, 28 were screened out (in a similar way as was done for the results from the first search), and 6 (all of which being conference proceedings) were not available through the lead authors' institutional repository.

After screening and removal of duplicates, the two literature searches yielded a combined total of 40 documents, which we analyzed by coding them with respect to the vehicle types considered, lightweighting strategies considered, vehicle components for which

Table 1
Coding categories for document analysis.

Vehicle types considered	• Microcar •Passenger car •Minivan/SUV •Light truck •Light commercial •Bus •Specific vehicle make and model (if noted)
Lightweighting strategies considered	•Materials substitution o High strength steels (HSS) o Advanced high strength steels (AHSS) o Ultra high strength steels (UHSS) o Aluminum alloys o Magnesium alloys o Plastics/polymers o Carbon fibre reinforced polymers (CFRP) o Other composites o Biobased materials •Lithium-oxygen batteries •Design changes (*e.g.*, "structural batteries")
Vehicle components for which lightweighting strategies are considered	•Body-in-white (BIW) •Glider (vehicle without powertrain and/or battery) •Closures •Structural components •Suspension components •Body components •Batteries •Wheels/tires •Braking system components •Electrical & electronic components •Engine/powertrain components •Seats •Acoustic/noise, vibration, and harshness (NVH) components
Methodological aspects of LCA	•Functional unit •Life cycle stages considered o Raw materials o Manufacturing o Use o End-of-life •Environmental impact categories evaluated o GHG emissions o Energy use o Ozone depletion o Acidification o Eutrophication o Human toxicity o Ecotoxicity o Photochemical oxidation (*i.e.*, smog formation) o Particulate matter formation o Resource use - Minerals & metals - Fossil fuels - Water - Land o "Societal life cycle cost" (Ogden et al., 2004)

lightweighting strategies are considered, and methodological aspects of LCA (Table 1).

3. Results

In this section, we outline and briefly discuss the results of our document analysis according to Table 1. Further details are provided in Supplementary Information.

3.1. Vehicle types considered

With respect to vehicle types, passenger cars are the most frequently considered in the literature, while larger vehicles, like light trucks, SUVs, light commercial vehicles, and busses, are occasionally considered (Table 2). This observation may reflect the fact that larger EVs like the Audi E-tron, Ford Mustang Mach-E, and Ford F150 Lightning have only recently been brought to market. As consumer preferences shift towards larger vehicles, and as electrification increasingly extends to heavier commercial vehicles like busses and semi trucks, lightweighting will become even more important.

3.2. Lightweighting strategies considered

Materials substitution, particularly with aluminum alloys, is the most frequently considered lightweighting strategy (Table 3). Notably, however, five articles consider what we have coded as "design changes" for EV lightweighting. These "design changes" include two concepts – "structural batteries" and wireless charging. For lack of a more precise definition, the essence of the "structural battery" idea is to design the battery pack as integral to the structure of the vehicle (Schuh et al., 2013). Zackrisson et al. (2019) consider integrating the battery into the vehicle roof. In commercial practice, "structural batteries" are being incorporated into, *e.g.*, the Texas-built Tesla Model Y, with its redesigned lithium-ion battery pack doubling as the central portion of the vehicle's lower structure (Munro & Associates, 2022; Perkins, 2020). Three studies, each with the same first author (Bi et al., 2015, 2017, 2018), consider wireless charging – for city busses – as a kind of lightweighting strategy. The idea is that, if bus stops are equipped with wireless charging capability, the bus can recharge somewhat at each stop, thereby enabling downsizing of the battery pack and ultimately lightweighting of the vehicle.

3.3. Vehicle components lightweighted

Closures (*e.g.*, doors, hoods, and trunk lids), vehicle body-in-whites (BIWs), and suspension components – none of which are unique to *electric* vehicles – are the most frequently considered vehicle components for EV lightweighting (Table 4). Lightweighting of high-voltage battery packs – which *are* unique to EVs – has received comparatively less attention, even though the battery pack is a major contributor to the weight of an EV. Increasing the size (*i.e.*, energy capacity) of the battery, to increase vehicle driving range, also increases overall vehicle weight, which in turn negatively impacts energy efficiency and range. Expert empirical analysis of commercially available EVs has found that vehicles with larger battery packs do not necessarily have longer range than those with smaller battery packs; much depends on the energy efficiency of the vehicle, which in turn is largely (though not entirely) a function of vehicle weight (Munro & Associates, 2021). Lightweighting – of the battery pack and the entire vehicle – is thus an important consideration in vehicle design, which would appear to have been largely overlooked by the LCA community.

Table 2
Vehicle types.

Vehicle types	Search 1	Search 2	TOTAL
Passenger car	16	3	19
Bus	4	0	4
Microcar	2	0	2
Minivan/SUV	1	0	1
Light truck	1	0	1
Light commercial	0	1	1

Note: Categories of vehicle types are not mutually exclusive (*i.e.*, the same document may consider multiple vehicle types), and some documents may not clearly specify a vehicle type. See Supplementary Information for further details.

Table 3
Lightweighting strategies considered.

Lightweighting strategies considered	Search 1	Search 2	TOTAL
Materials, aluminum alloys	15	6	21
Materials, carbon fibre reinforced polymers (CFRP)	7	3	10
Materials, advanced high strength steels (AHSS)	5	3	8
Materials, magnesium alloys	3	3	6
Materials, plastics/polymers	5	0	5
Design changes	5	0	5
Materials, high strength steels (HSS)	2	2	4
Materials, biobased	2	1	3
Materials, other composites	0	2	2
Materials, ultra high strength steels (UHSS)	1	0	1
Materials, lithium-oxygen batteries	0	1	1

Note: Categories of lightweighting strategies are not mutually exclusive (*i.e.*, the same document may discuss multiple lightweighting strategies), and some documents may not clearly specify a lightweighting strategy(ies). See Supplementary Information for further details.

Table 4
Vehicle components lightweighted.

Vehicle components lightweighted	Search 1	Search 2	TOTAL
Closures	4	2	6
Body-in-white (BIW)	4	1	5
Suspension components	3	2	5
Structural components	1	2	3
Body components	1	2	3
Batteries	2	1	3
Glider (vehicle without powertrain and/or battery)	2	0	2
Wheels/tires	0	1	1
Braking system components	0	1	1
Electrical & electronic components	0	1	1
Engine/powertrain components	0	1	1
Seats	0	1	1
Acoustic/noise, vibration, and harshness (NVH) components	0	1	1

Note: Categories of vehicle components lightweighted are not mutually exclusive (*i.e.*, the same document may discuss lightweighting of multiple vehicle components), and some documents may not clearly specify which components are lightweighted. See Supplementary Information for further details.

3.4. Methodological aspects of LCA

As can be seen in Table 5, GHG emissions and energy use are the most frequently evaluated environmental impact categories (noting that, strictly speaking, neither are proper LCA impact categories; the impact category corresponding to GHG emissions is "global warming potential" or "climate change," and energy use is not an environmental impact in itself). Results are mixed. On the one hand, in their analysis of the Multi Material Lightweight Vehicle concept, Luk et al. (2018) found probable reductions of life cycle GHG emissions amounting to 10 t CO_2 eq. for an ICEV, 6 t CO_2 eq. for an HEV, and 7 t CO_2 eq. for a BEV. On the other hand, in their analysis of lightweighting and other material efficiency strategies, Wolfram et al. (2021) found that with current global energy supply, the contribution of lightweighting (with aluminum alloys) to GHG emissions reduction is modest, or even slightly negative, ranging

Table 5
Environmental impact categories considered.

Environmental impact categories considered	Search 1	Search 2	TOTAL
GHG emissions	27	3	30
Energy use	11	3	14
Photochemical oxidation (smog formation)	8	1	9
Acidification	6	1	7
Eutrophication	6	1	7
Ozone depletion	5	1	6
Human toxicity	5	1	6
Resource use, minerals and metals	5	1	6
Ecotoxicity	4	1	5
Particulate matter formation	3	1	4
Resource use, fossil fuels	2	1	3
Resource use, water	1	1	2
Resource use, land	0	1	1
Societal life cycle cost	1	0	1

Note: Environmental impact categories considered are not mutually exclusive (*i.e.*, the same document may consider multiple categories), and some documents may not clearly specify the impact categories considered. See Supplementary Information for further details.

from −3 to +4%. The limited, or even negative, effect of EV lightweighting on GHG emissions reduction is due in part to the tendency of "lightweight" materials, like aluminum alloys, to have higher embodied emissions than the materials (typically steel) they replace (Wolfram et al., 2021). Notably, both studies, as observed elsewhere, suggest that the benefit of lightweighting is smaller for EVs in comparison to ICEVs.

Vehicle end-of-life is notably less frequently considered than other life cycle stages (Table 6); this observation may reflect the present reality that, as EVs are still relatively new, have generally proven to be reliable and long-lasting (Najman, 2023), and still account for only a small share of the overall vehicle fleet, the volumes of EVs reaching end-of-life have been relatively small (Reid, 2022).

Only seven documents, all from the first search, evaluate multiple environmental impact categories over the whole life cycle of a whole vehicle. Among these documents, an article by Upadhyayula et al. (2019) presents an LCA of lightweighted ICEVs and an LCA of EVs, but not an LCA of *lightweighted EVs*. Though an article by Zackrisson et al. (2019) considers multiple environmental impact categories, these categories are limited to GHG emissions, photochemical oxidation (*i.e.*, smog formation), and mineral resource use. Other widely recognized environmental impact categories, like acidification, eutrophication, and ecotoxicity, are not considered. An article by Shanmugam et al. (2019) presents a cradle-to-grave LCA of lightweighted ICEVs and EVs, but only for the BIW (although this is a major part of the vehicle). An article by Ding et al. (2021) is similarly limited to the BIW. An article by Mayyas et al. (2017) addresses only energy use and GHG emissions. Finally, an article by Delogu et al. (2017) considers lightweighting of the BIW, other structural components, suspension components, and closures – but this still does not constitute a whole-vehicle LCA. Ultimately, we did not find a single LCA study of EV lightweighting that evaluates a comprehensive set of environmental impact categories (*i.e.*, considering emissions to air, water, and soil) over the whole life cycle of a whole vehicle. From an LCA perspective, this research gap is important because, as we noted in the introduction to this article, lightweighting can create trade-offs in environmental impacts between impact categories and between life cycle stages. We will elaborate on this point in our discussion.

Table 6
Life cycle stages considered.

Life cycle stages considered	Search 1	Search 2	TOTAL
Raw materials	19	4	23
Use	20	3	23
Manufacturing	18	4	22
End-of-life	10	3	13

Note: Categories of life cycle stages considered are not mutually exclusive (*i.e.*, the same document may consider multiple life cycle stages), and some documents may not clearly specify which life cycle stages are considered. See Supplementary Information for further details.

4. Discussion

Our discussion is structured as follows. In section 4.1, we reflect on the significance of our scoping review results – particularly our observation that not one of the 40 documents we reviewed constitutes an LCA of EV lightweighting that evaluates a comprehensive set of environmental impact categories (*i.e.*, considering emissions to air, water, and soil) over the whole life cycle of a whole vehicle. In section 4.2, we consider the limitations of our scoping review. In section 4.3, we provide an outlook on future research directions.

4.1. Significance of our scoping review results

Remarkably, our comprehensive scoping review – comprising two systematic literature searches across multiple research databases – did not find a single LCA study of EV lightweighting that evaluates a comprehensive set of environmental impact categories (*i.e.*, considering emissions to air, water, and soil) over the whole life cycle of a whole vehicle. This is a major weakness of the current evidence base on the environmental implications of EV lightweighting, as it means that trade-offs – between life cycle stages or between environmental impact categories – cannot be evaluated or incorporated into decision-making (*e.g.*, in vehicle design and public policy).

In fairness, the existing literature does recognize potential trade-offs between life cycle stages (*e.g.*, "lightweight" materials like aluminum and CFRP, while reducing energy use and environmental impacts from vehicle operation, may have higher impacts from their production (Delogu et al., 2017; Lewis et al., 2019; Wolfram et al., 2021; Zanchi et al., 2016)). Further, the literature highlights a key observation about *electric* vehicle lightweighting, in comparison to lightweighting of internal combustion vehicles: the inherently higher energy efficiency of an EV compared to an ICEV results in comparatively smaller efficiency improvements from lightweighting – termed "mass elasticity of fuel consumption," "weight-induced energy savings," or "fuel reduction value" – for an EV (Garcia and Freire, 2017; Kim and Wallington, 2016; Lewis et al., 2014; Luk et al., 2017, 2018; Shanmugam et al., 2019). Combined with the tendency for "lightweight" vehicle materials to have higher environmental impacts than the conventional materials they replace, a smaller improvement in operational energy efficiency from lightweighting of an EV, compared to an ICEV, could tip the balance of the trade-off – between the production and use stages of the vehicle life cycle – against lightweighting, such that increased environmental impacts from vehicle production exceed reductions in impacts from the vehicle use phase (Luk et al., 2017, 2018; Shanmugam et al., 2019). This observation points to the need to consider EV lightweighting approaches differently than strategies employed for conventional vehicles.

However, our review indicates that potential trade-offs *between impact categories* are widely overlooked. This oversight is particularly concerning given that previous LCA studies of EVs, in comparison to ICEVs (Gan et al., 2023; Hawkins et al., 2013), have found *actual* trade-offs between impact categories (particularly between GHG emissions and air pollutants, on the one hand, and eutrophication and ecological toxicity, on the other). Further, and particularly important for EVs, considerations of resource use, including supply of critical raw materials, have been largely under-emphasized in the existing literature.

Along with trade-offs, a more systematic and comprehensive evaluation of EV lightweighting could also reveal co-benefits, environmentally and otherwise. Reducing vehicle weight could help reduce some types of emissions, like those from road and tire wear, that EVs can otherwise be expected to increase in comparison to ICEVs (although, despite the greater weight of EVs, emissions from brake wear are likely reduced due to regenerative braking) (Ritchie, 2023). Reduced road and tire wear not only results in lower emissions of road and tire particles – which, if allowed to increase due to the greater weight of EVs, would somewhat counter the notion that EVs reduce local pollution – it also results in lower needs for repair and replacement of roads and tires, given their extended lifespan. Moreover, looking beyond environmental impacts, reducing the weight of EVs has safety benefits for road users. Although greater vehicle weight may be an advantage for vehicle occupants in the event of a collision, heavier vehicles put other motorists, and especially vulnerable road users like cyclists and pedestrians, at increased risk (Proskow, 2023). Therefore, as we have previously stated, lightweighting is especially important – and different – for EVs, and EV lightweighting needs further study by the LCA community.

4.2. Limitations of our review

Like any literature survey, our review has limitations. First, we may have missed relevant literature that does not use our search terms. For example, an article using terms like "carbon footprint" or "life cycle greenhouse gas emissions" may not be found. Using such terms could broaden our search results considerably, though our central finding – that there is a lack of full LCA studies of EV lightweighting – would probably not change. One recent study, which is broadly relevant to the topic at hand, though not included in our search results, is a fleet-level life cycle GHG emissions modelling exercise by Milovanoff et al. (2019), from which the authors concluded that lightweighting of light-duty vehicles in the USA, using aluminum alloys or high-strength steels, is likely to yield fleet-level GHG emission reductions (noting that the aforementioned trade-offs with other types of environmental impacts are not addressed).

Our search terms may also have biased our review towards lightweighting through materials substitution (particularly in search 2), which might partially explain why we found material substitutions to be the dominant lightweighting strategies (section 3.1). On this point, however, we reiterate our observation that five documents consider lightweighting strategies we coded as "design changes; " these lightweighting strategies include the use of "structural batteries" and wireless charging (for city busses). Another "design change" idea, which we did not find in the literature surveyed, is to design some form of modular battery pack – perhaps an EV could have a "main" pack supplemented by an "extra" pack that is used only when longer range is needed.

We also note that "grey" literature, like government and industry reports, is not well covered by our review, largely because non-scholarly literature is not indexed like academic articles. Further, we have not performed a systematic quality evaluation of the academic literature surveyed. Nonetheless, as detailed in Supplementary Information, we frequently observed several indicators of poor quality from an LCA perspective (in addition to a narrow selection of environmental impact categories), such as missing or unclear functional unit definition, lack of clarity around system boundaries, and the omission of numerical LCA results in non-normalized form. These weaknesses and inconsistencies in the existing literature make it difficult to interpret study results, compare findings, and draw generalized conclusions. Finally, given that our review considered only English language literature, we may be missing relevant sources and discussion in other languages. China, in particular, is the largest EV producing nation and consumer market. Relevant articles on lightweighting that are available only in the Chinese language would not be covered in our review.

4.3. Outlook on future research directions

To reiterate, our review highlights the need for future research on EV lightweighting from an LCA perspective – evaluating a comprehensive set of environmental impact categories (*i.e.*, considering emissions to air, water, and soil) over the whole life cycle of a whole vehicle. It may also be worth further investigating potential trade-offs and co-benefits beyond the vehicle itself, and beyond environmental impacts. For example, as we noted in the previous section, lightweighting of EVs could help reduce the environmental impacts of road and tire wear, which, without lightweighting, EVs are likely to increase due to their greater weight compared to internal combustion vehicles. Though beyond the scope of conventional LCA, which focuses on *environmental* impacts, the implications of EV lightweighting for the safety of vulnerable road users are also important considerations in vehicle design and public policy.

Along with technological solutions, a rather obvious means of lightweighting is to reduce vehicle size. Over the last decades, light-duty vehicles have, on average, grown larger and heavier (Bubbers, 2023). Especially in North America, the market is increasingly shifting towards larger SUVs and trucks over smaller and more efficient passenger cars (Bubbers, 2023; Cozzi and Petropoulos, 2021); a growing number of automakers are dropping passenger cars from their product portfolio (Eisenstein, 2018; Noguchi et al., 2023; Olsen, 2018). In the case of EVs, there is also the option of reducing battery size, somewhat independently of vehicle sizing. However, this option is challenged by consumer demand for vehicles with maximum driving range, regardless of how often (or seldom) such range is actually needed. Hence, lightweighting and other technical strategies for reducing the environmental impacts of personal mobility need to be accompanied by changes in consumer and societal behaviour.

5. Conclusion

We have conducted a comprehensive scoping review of the existing literature on lightweighting of electric vehicles (EVs) from an LCA perspective, based on two systematic searches across multiple research databases. Our analysis of this literature indicates that, from an LCA perspective, EV lightweighting has been considered primarily with respect to comparatively smaller vehicles (*e.g.*, passenger cars as opposed to light trucks and heavier commercial vehicles), and for vehicle components shared with internal combustion vehicles (*e.g.*, closures, body-in-white, and suspension components). Greenhouse gas emissions and energy use are the most frequently evaluated environmental impact categories, while vehicle end-of-life is less frequently considered than other life cycle stages. Ultimately, we did not find a single LCA study of EV lightweighting that evaluates a comprehensive set of environmental impact categories, for a whole vehicle, over the whole vehicle life cycle (*i.e.*, from production through end-of-life). We recommend that further research on lightweighting consider the characteristics of *electric* vehicles while better evaluating environmental impacts and resource use (*e.g.*, regarding critical raw materials supply), considering trade-offs and co-benefits. For example, we have highlighted opportunities like reducing vehicle and battery size, although these valuable strategies need to be accompanied by changes in consumer and societal behaviour.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Steven B. Young reports financial support was provided by Natural Resources Canada.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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