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Life Cycle Assessment studies on lightweight materials for automotive applications - An overview

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Abstract

Lightweight materials have the potential to reduce vehicle fuel consumption and emissions. This study critically reviews Life Cycle Assessment (LCA) studies focused on lightweight materials (Advanced and High-Strength Steels (A/HSS), Aluminium (Al), Magnesium (Mg), and composites) for automotive chassis and body-in-white components, to identify the materials with the lowest environmental impacts, trends and improvement opportunities. Since most impacts are associated with the vehicle use-stage (due to fossil fuel consumption), lightweight materials have environmental benefits in a cradle-to-grave approach. Greenhouse gas (GHG) emissions and energy consumption are the most reported impact categories. Several studies simplify their inventory and overuse assumptions, which lead to higher results uncertainty. In addition, the primary and secondary mass reductions, recycling rates and driven distances have been identified as crucial hotspots. A/HSS is identified as the most preferable lightweight material, followed by Al. However, there is a lack of scientific consensus. To formulate sound conclusions, this review recommends that future studies should present clearer inventory data, GHG break-even driving distances, uncertainty and/or sensitivity analysis, as well as consider secondary mass reductions and assess other impact categories to unveil more hotspots for improvements. When substantial technology change is assumed, consequential LCA should be used to assess the predictive market uptake.

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Keywords: Life Cycle Assessment; Literature review; Vehicle's lightweight materials

Abbreviations: A/HSS, Advanced and High-Strength Steels; AHSS, Advanced High-Strength Steel; Al, Aluminium; BEV, Battery Electric Vehicle; BIW, Body-in-White; C/GFRP, Carbon and Glass Fibre Reinforced Plastic; CFRP, Carbon Fibre Reinforced Plastic; C-LCA, Consequential Life Cycle Assessment; EoL, End-of-Life; FU, Functional Unit; GFRP, Glass Fibre Reinforced Plastic; GHG, Greenhouse Gas; HEV, Hybrid Electric Vehicle; HSS, High-Strength Steels; ICEV, Internal combustion enginevehicle; ICV, Internal Combustion Vehicle; LC, Life Cycle; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; Mg, Magnesium; MS, Midsize Sedan; PHEV, Plug-in Hybrid Electric Vehicle; SF6, Sulphur Hexafluoride; SUV, Sport-Utility Vehicle; TR, Pickup Truck

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1. Introduction

Most vehicle life cycle (LC) energy and greenhouse gas (GHG) emissions are associated with its use-stage: 84%–91% [1]. Lightweight materials can enable a reduction of 23% in fuel consumption at the use-stage due to vehicle mass reduction [2]. This study critically reviews Life Cycle Assessment (LCA) studies focused on lightweight materials (Advanced and High-Strength Steels (A/HSS), Aluminium (Al), Magnesium (Mg), and composites) for automotive chassis and body-in-white (BIW) components. The goal is to identify the vehicle's lightweight materials with the lowest environmental impacts, some trends and improvement opportunities. The literature review has been structured as followed: Review of the LCA studies; Discussion of the findings; Recommendations and Conclusions.

2. Literature review of LCA vehicle's lightweight materials

This review study addresses the components, chassis and BIW, and lightweight materials that can contribute to a major vehicle mass reduction [3], namely, High-Strength Steels (HSS), Advanced High-Strength Steel (AHSS), Al, Mg and Composites. The bibliographic review methodology adopted followed the search of specific terms in the title, abstract and keywords of the scientific papers, namely "HSS" or "AHSS" or "Al" or "Mg" or "Composites"; and "vehicle" and "lightweight" and "LCA", by using different search engines (e.g. Science Direct and Google) in the last trimester of 2020. In addition, the authors selected and prioritized the studies that included a comparison between lightweight materials applied mainly to chassis and BIW components following a cradle-to-grave approach (a total of 12 studies). LCA is a methodology to assess the potential LC impacts (ISO 14040:2006; 14044:2006) that enables to track the environmental impacts trade-offs, e.g. shift of lightweight materials impacts between LC stages. In the following subchapters, the LCA studies are analysed concerning the type of lightweight material reported as having the best environmental performance. Detailed support information is provided in Table 1 for each study under analysis, regarding the key-parameters used (namely lightweight materials, LC stages, Functional Unit (FU), driven distance, sensitivity analysis, recycling, weight reduction, powertrain and LCA methods), scenarios studied, and impact values achieved.

2.1. Review of aluminium

Das [8] performed a cradle-to-grave analysis of different BIW lightweight designs for a Toyota Venza vehicle model, namely a baseline model (steel and HSS), compared to AHSS and Al. Al design presented the best GHG break-even distance and a higher potential to improve LC energy and GHG emissions. The author found that AHSS requires a larger driven distance (76.000 km) than Al (19.000 km) to offset the GHG emissions of material production LC stage (GHG break-even distance). The study also remarked two constraints related to Al, the need to overcome its higher manufacturing energy consumption and more demanding End-of-Life (EoL) recycling rates. Raugei et al. [12] used the CML method to quantify a set of environmental impacts (Table 1) of a baseline Volkswagen Polo (HSS) compared to Al, Mg and carbon fibre reinforced plastic (CFRP). The Al components had the best environmental performance, with an exception for human toxicity (related to Al extraction and production processes). By having other impact categories, besides GHG and energy, this study showed that the best/worst alternative may vary with the impact categories considered. Stasinopoulos [13] performed a consequential energy LC study to account for temporal effects (e.g. availability of recycled Al in the market). The authors compared a BIW made of steel and Al and considered two approaches: a product-based and a fleet-based (over 100 years; initially the fleet only contained BIWs made of steel, which was gradually displaced by Al). The product-based results indicated that Al consumes less energy than steel over a single-vehicle LC (overestimated the Al short-term benefits). The fleet-based analysis suggested that this benefit of Al took some time to be significant in a fleet-based approach (at least over 30 years), i.e. increasing the amount of Al components in the market will probably lead to a gradual increment in the Al recycling rates overtime and to the stock of pre-existing steel components to decay out of the fleet.

Table 1. Summary of the literature review regarding the LCA studies about vehicle lightweight materials.

Ref.	Summary of key-parameters, scenarios, and impact values[a]
[4]	**Materials**: AHSS, Al, mild steel; **LC Stages**: Cradle-to-grave; **FU**: Light duty truck; **Driven distance**: 200.000–300.000 km; **Sensitivity**: km, powertrain; fuel savings; **Recycling**: Yes; **Weight**: 240 kg mass savings; **Powertrain**: gasoline; **Methods**: UCSB — Automotive Materials Energy and GHG Comparison Model v4; **Scenarios**: The manufacturer expects to save 240 kg by replacing mild steel with Al in the BIW, closures, and bed. Alternative design using AHSS; **Impact values**: Mild steel: 72.064–103.334 kg CO_2; AHSS: 68.973–101.526 kg CO_2; Al: 70.533–103.602 kg CO_2.
[5]	**Materials**: AHSS, Al, steel; **LC Stages**: Cradle-to-grave; **FU**: SUV; **Driven distance**: N/A; **Sensitivity**: km, fuel savings, powertrain; **Recycling**: N/A; **Weight**: Al 32% mass savings and AHSS 25%; **Powertrain**: N/A; **Methods**: UCSB model; **Scenarios**: The manufacturer expects to save 300 kg by replacing conventional steel with Al and AHSS in the body structure, closures, suspension, and subframes; **Impact values**: Best case scenario: Al reduces in 1.000 kg CO_2 of baseline SUV, while AHSS reduces by over 3.000 kg CO_2 emissions. Worst case scenario: Al savings in CO_2 emissions near 300 kg, being savings higher for AHSS.
[6]	**Materials**: AHSS, HSS, Al, Mg, CFRP; **LC Stages**: Cradle-to-grave; **FU**: door frame and chassis; **Driven distance**: 260.000 km; **Sensitivity**: km, powertrain; **Recycling**: N/A; **Weight**: different ratios; **Powertrain**: Gasoline; **Methods**: GREET; **Scenarios**: passenger Vehicle 2-ICEV (Internal combustion engine vehicle) parts. LCI assume same values for steel, HSS, and AHSS with respect to energy and GHG; **Impact values**: Chassis: energy (GJ): Al 109; Mg 110; HSS 109; AHSS 109; GHG (g CO_2): Al 7.940; Mg 7.950; HSS 7.900; AHSS 7.900. Door frames: energy (GJ): Al 111; Mg 112; HSS 109; AHSS 108; CFRP 114; GHG (g CO_2): Al 8.000; Mg 8.060; HSS 7.890; AHSS 7.860; CFRP 8.170.
[7]	**Materials**: AHSS, Al, Mg, C/GFRP; **LC Stages**: Cradle-to-grave; **FU**: kg of BIW; **Driven distance**: 200.000 miles; **Sensitivity**: km, fuel savings, recycle %; **Recycling**: Steel 90%, Al and Mg 95%, C/GFRP 1%; **Weight**: 203 kg AHSS, 135 Al, 100 Mg, 123 composites; **Powertrain**: gasoline; **Methods**: GREET; **Scenarios**: Mid-size passenger BIW. Manufacturing and assembly processes are assumed to be similar for all metals. The powertrain can meet the performance requirements by adjusting the engine size; **Impact values**: AHSS: 937 MJ/kg, 66 kg CO_2/kg; Al: 881 MJ/kg, 65 kg CO_2/kg; Mg: 888 MJ/kg, 64 kg CO_2/kg; Composites: 1.138 MJ/kg, 77 kg CO_2/kg.
[8]	**Materials**: Al, AHSS, HSS, steel; **LC Stages**: Cradle-to-grave; **FU**: total vehicle mass; **Driven distance**: 250.000 km; **Sensitivity**: km; **Recycling**: Scrap steel 95.3%, 98%; **Weight**: baseline (1711 kg), AHSS (1453 kg), Al (1290 kg); **Powertrain**: gasoline fuel containing 10% ethanol; **Methods**: TRACI; **Scenarios**: lightweight vehicle designs are evaluated: Baseline (steel and HSS), AHSS, Al of mid-size crossover sport utility vehicle (Toyota Venza BIW and closures) operated today in North America. No LCI distinctions were made between conventional steels and AHSS. Include secondary mass reductions of the engine, transmission, and wheels; **Impact values**: Baseline: Global warming 76.397 kg CO_2; Acidification 56 kg SO_2; eutrophication 3 kg N; Smog 1563 kg O_3; Respiratory effects 7 kg PM2.5; Ozone depletion 2.92E-5 kg CFC-11. AHSS: Global warming 67.777 kg CO_2; Acidification 47 kg SO_2; eutrophication 2 kg N; Smog 1348 kg O_3; Respiratory effects 6 kg PM2.5; Ozone depletion 4.15E-5 kg CFC-11. Al: Global warming 63.412 kg CO_2; Acidification 48 kg SO_2; Eutrophication 2 kg N; Smog 1276 kg O_3; Respiratory effects 6 kg PM2.5; Ozone depletion 1.28E-5 kg CFC-11.
[9]	**Materials**: Steel, HSS, Al, C/GFRP; **LC Stages**: Cradle-to-grave; **FU**: BIW; **Driven distance**: 225.000 km; **Sensitivity**: fuel savings, km, EoL scrap, recycling; **Recycling**: Steel, HSS-39%; Al-43%; Extra material part production: Steel, HSS +40%; Al +40% (rolling), +10% (extruding), +10% (casting); GFRP + 5%; CFRP +20%; **Weight**: Benchmark (1250 kg), multi-material (1144 kg), Al (1090 kg), composite (956 kg); **Powertrain**: 6.9 l/100 km; **Methods**: Equations (Energy, Waste generation); **Scenarios**: Multi-parametric comparison of the life cycle energy use and waste generation of current mid-class compact passenger. Benchmark (mild steel and HSS), multi-material (HSS, Al, CFRP), Al and composite. Car assembly and maintenance are ignored; **Impact values**: Multi-material: Energy reductions 3,8–3,9%; Waste 34,7–46,8 kg; Al: Energy reductions 3,1–3,4%; Waste 59,0 kg. Composite: Energy reductions 9,3–9,7%; Waste 0–178,9 kg.

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2.2. Review of advanced and high-strength steels

The World Steel Association [5] reported that in a cradle-to-grave approach for a baseline BIW of a light-duty truck (mild steel), AHSS had lower GHG emissions when compared to Al. By running 5.000 iterations for a range of factors (sensitivity analysis: Table 1) AHSS decreased its GHG emissions in the best and worst-case scenarios. While Al achieved no reduction in LC emissions in the worst scenario and even higher than the baseline BIW (mild steel). The analysis was extended to a sport-utility vehicle (SUV) [5]. Despite AHSS had the best LC GHG emissions, at the use-stage Al fuel savings (0,5–0,9 l/100 km) were higher than AHSS (0,1–0,2 l/100 km). However,

Table 1 (*continued*).

Ref.	Summary of key-parameters, scenarios, and impact values[a]
[10]	**Materials**: Mg, Al; **LC Stages**: Cradle-to-grave; **FU**: one steering wheel; **Driven distance**: 200.000 km; **Sensitivity**: km, Mg production; **Recycling**: 97% for both alloys; **Weight**: 26% reduction; **Powertrain**: gasoline; **Methods**: CML; **Scenarios**: Mg component production (steering wheel frame produced via die casting) for a gasoline passenger vehicle compared to Al. Cover gas types: SF6, SO_2, R134a; **Impact values**: Overall balance for Mg compared to Al, Δ kg CO_2: Pidgeon average −2,5; Pidgeon average incl. credits −3,5; Electrolysis −3,9; Electrolysis incl. credits −4,6.
[11]	**Materials**: AHSS, Al, Steel; **LC Stages**: Cradle-to-grave; **FU**: Vehicle; **Driven distance**: passenger car 245.000 km, truck 290.000 km; **Recycling**: Rolled Al 50%, Extruded/Cast Al. 80%, Flat Carbon Steel and AHSS 55%; **Sensitivity**: parameters optimization; **Weight**: Replacement coefficient: AHSS 0,75; Al 0.65; **Powertrain**: depends on vehicle model; **Methods**: UCSB model; **Scenarios**: Lightweight contender vehicles: AHSS and Al compared to baseline vehicle (steel). Vehicle models: MS (midsize sedan), SUV, TR (pickup truck), HEV (hybrid electric vehicle) and BEV (battery electric vehicle); **Impact values**: GHG kg CO_2/vehicle: Contender, AHSS 54.558; Al 55.064. SUV AHSS: 75.777; Al 76.504. TR, AHSS 86.141; Al 86.672. HEV, AHSS 39.797; Al 40.499. BEV, AHSS 26.237; Al 26.714.
[1]	**Materials**: Al, AHSS, HSS; **LC Stages**: Cradle-to-grave; **FU**: per-mile basis; **Driven distance**: 160.000 miles; **Sensitivity**: Amount of primary vs. secondary Al; electric grid; **Recycling**: 11% secondary Al in wrought products and 85% recycled Al in cast products. 26% of the steel content is made from recycled materials; **Weight**: 15% and 20% with AHSS and 15%, 20%, 25% and 35% with the Al; **Powertrain**: re-sizing; **Methods**: GREET; **Scenarios**: BIW mass reduction with Al and AHSS compared to a baseline (HSS). Vehicles: internal combustion vehicle (ICV), HEV and plug-in hybrid electric vehicle (PHEV). It is assumed secondary mass reductions and that no additional energy is required for AHSS as compared to HSS; **Impact values**: ICV: Al, 350–370 g GHG/mi and 4,6–4,9 MJ/mi. AHSS, 358–360 g GHG/mi and 4,7–4,8 MJ/mi. HEV: Al, 251–265 g GHG/mi and 3,3–3,5 MJ/mi. AHSS, 253–256 g GHG/mi and 3,4 MJ/mi. PHEV: Al, 230–243 g GHG/mi and 3,0–3,2 MJ/mi. AHSS, 231–234 g GHG/mi and 3,0–3,1 MJ/mi.
[12]	**Materials**: Al, Mg, CFRP, HSS; **LC Stages**: Cradle-to-grave; **FU**: segment car; **Driven distance**: 150.000 km; **Sensitivity**: Driving cycle, EoL scenarios, Mg production (vary the SF6 emissions); **Recycling**: EoL current European Union legislation for recycling and landfill; **Weight**: −50% for Al, −60% Mg and −70% CFRP; **Powertrain**: 44 kW Volkswagen petrol engine; **Methods**: CML; Scenarios: Lightweighting options for a Volkswagen Polo using Al, Mg and CFR compared to a baseline (HSS). Secondary weight reductions not considered. EoL scenarios: pessimistic (higher landfill) and optimistic (higher recycling, thus replacement of virgin material); **Impact values**: Al, Energy: 423.077–525.641 MJ; GHG: 28.649–35.675 kg CO_2; Acidification: 73–91 kg SO_2; Toxicity: 8.814–13898 kg DCB ($C_6H_4Cl_2$). Mg, Energy: 455.128–557.692 MJ; GHG: 29.730–50.270 kg CO_2; Acidification: 79–114 kg SO_2; Toxicity: 4.333–8.000 kg DCB. Composite, Energy: 437.500–544.643 MJ; GHG: 28.267–36.267 kg CO_2; Acidification: 72–96 kg SO_2; Toxicity: 7.241–12.414 kg DCB.
[13]	**Materials**: Steel, Al; **LC Stages**: Cradle-to-gate; **FU**: BIW product-based and fleet-based over 100 years; **Driven distance**: 300.000 km (useful life 19 years); **Sensitivity**: key assumptions; **Recycling**: Steel 25%, initial Al 10% (% will vary along with the demand for new cars); **Weight**: Steel 430 kg, Al 300 kg; **Powertrain**: N/A; **Methods**: STELLA; **Scenarios**: BIW made from steel and Al in Australia. C-LCA: a single fleet initially containing only steel BIWs is gradually displaced by Al BIWs. When the recycling loop is disabled, recovery is 0%; when the recycling loop is enabled, recovery is assumed to be 90%; **Impact values**: product-based: Al has 17% less energy than steel. Fleet-base: energy benefits of Al BIWs do not begin to emerge until year 31. At year 100, 84% of Al BIWs are being produced from recycled content, Al is less energy-intensive (17%–27%) than steel.
[14]	**Materials**: HSS, Al; **LC Stages**: Cradle-to-grave; **FU**: vehicle; **Driven distance**: 181.195 miles; **Sensitivity**: key assumptions; **Recycling**: steel 95%, Al 89%. Scrap: steel 95%, Al 91%; **Weight**: 6% mass reduction (Al, HSS), 11% (Al), 19% (HSS) and 23% (Al); **Powertrain**: gasoline; **Methods**: IPCC; **Scenarios**: BIW of a compact sized Ford Focus ZX3 vehicle made of Al and HSS, both compared to a baseline. Secondary weight reductions are considered; **Impact values**: HSS has higher GHG savings than Al at 6% and 19% mass reduction. HSS has significantly lower GHG emissions (1 to 3 years payback times[b]) than 23% Al (4 to 10 years payback times) in the production phase.

[a]Some impact values of graphics were obtained by using the measuring tool of Adobe Acrobat.

[b]Payback time: how many years of vehicle use are required to offset the added GHG emissions from the production stage.

at the production stage Al had seven times more GHG emissions, which were not offset in use-stage. Kelly et al. [6] also concluded that AHSS had lower LC GHG emissions than Al, Mg and CFRP. Compared to the baseline 2-ICEV vehicle (HSS) wrought Al, Mg, or CFRP resulted in increased GHG emissions. Al GHG emissions varied with the Al type (cast enables reductions in weight and GHG, wrought reduces weight but increases GHG). Mg GHG emissions were related to its production process: use of sulphur hexafluoride (SF6) as a cover gas. Though, as in other studies (Table 1), the Life Cycle Inventory (LCI) used was the same for HSS and AHSS production which can potentially benefit the AHSS, since different alloys have different impacts. Kim et al. [14] quantified the GHG emissions of all LC stages of a Ford Focus ZX3 BIW made of Al or HSS. Considering the actual EoL status of steel and Al, the results showed that HSS required lower payback times to offset the GHG emissions. Al payback times could be shortened if a closed-loop recycling scheme is implemented but accordingly to the authors until 2025 it is unlikely to happen. A constraint identified was the lower HSS GHG break-even distance than Al, associated with the rates of mass reduction, e.g. for 6% mass reduction: HSS 9.500 miles; Al 54.500 miles. Mayyas el al. [7] achieved a similar conclusion for a BIW made of AHSS, Al, Mg, CFRP and glass fibre reinforced plastic (GFRP). When the useful lifetime is low ($\leq$ 100.000 miles), AHSS performed better than Al and Mg. However, this preference changed to Al and Mg when the lifetime exceeds 100.000 miles. While, the composites had the worst energy and GHG performance due to their shorter lifetime and near-zero recyclability. Regarding the vehicle type, the Steel Market Development Institute [11] and Lewis et al. [1] considered AHSS and Al as lightweight materials and different vehicle models (Table 1). AHSS had the highest GHG savings for all the vehicle models. Regarding the type of vehicle (powertrain), Lewis et al. [1] highlighted that lightweight materials are more useful in vehicles with more burdens in use-stage, e.g. combustion vehicle vs. hybrid.

2.3. Review of magnesium

Ehrenberger [10] assessed the entire LC of an Mg steering wheel frame produced for a gasoline passenger vehicle compared to Al. The authors concluded that Mg had lower impacts due to the lower rates of Mg material to be processed (higher mass reduction rates), which implied a lower energy consumption. A sensitivity analysis showed that Mg production impacts strictly depended on the process type considered (Pidgeon process had higher GHG emissions than electrolysis due to SF6 emissions).

2.4. Review of composites

Tempelman et al. [9] studied the energy consumption and waste generation of Al, CFRP and multi-material (HSS, Al and CFRP) of a mid-class compact passenger car. By assuming full waste incineration, CFRP had the highest potential for LC energy reductions, which accordingly to the authors would also be environmental better for reducing solid waste at EoL stage.

3. Discussion

Most of the studies pointed out environmental benefits associated with the production and use-stage of lightweight materials when compared to conventional steel. GHG emissions and energy consumption are the most reported impact categories (which have a similar trend, since GHG emissions are strictly related to energy consumption). However, this trend could not be reliable for other environmental impact categories, such as toxicity [12]. Al is the most common lightweight material included, followed by A/HSS, Mg and composites. Use-stage dominates the overall impact results (due to fossil fuel consumption), followed by the material production stage.

For Al the studies reported that its lowest impacts are related to its potential to achieve the highest mass reduction rates, which directly decreased fuel consumption in the vehicle use-stage [8,12]. It was possible to identify two main bottleneck factors, namely its highest manufacturing energy consumption [1,5] which was mitigated when considering all-LC stages (significance of the use-stage to total impacts) and its current low EoL recycling rates [6] (critical factor for Al to be competitive since the steelmaking industry has already a well-established recycling industry [8]). Though hypothetical recycling rates were considered for Al, based on the assumption that Al market expansion will trigger similar rates of the steel market.

A/HSS lower impacts were related to a lower energy-intensive production process and to its highest recycling rates. The steel EoL scenarios reflected the current recycling practices (recycling rates of 80%–95%). Besides, when multi-material design options were considered A/HSS stood out because it can be separated by magnets at the EoL stage. However, some studies for A/HSS production assumed the same energy consumption and GHG emissions than for conventional steel and for both alloys (HSS and AHSS) [1,6], which can potentially benefit the A/HSS alloys.

Despite the credits given by Ehrenberger [10] to Mg lightweight material, more constraints were found in the literature reviewed. The impact reduction in the vehicle use-stage (due to vehicle mass reduction) did not offset the

Mg production stage impacts [6,7,12]. The environmental benefits of using Mg appeared to be more ambiguous and strongly depend on two factors: achieving the complete phase-out of SF6 and the establishment of a separate closed-loop recycling scheme (recycling deficit processes). Accordingly, to Raugei et al. [12] only under the most favourable scenario, i.e. assuming a complete phase-out of SF6 worldwide and 90% EoL closed-loop recycling, the Mg achieved a modest GHG emissions reduction (2%–4%) against the baseline (HSS). In addition, Mg had higher acidification impacts than HSS, even in the optimistic scenario. However, nowadays processing plants can use other cover gases (sulphur dioxide, R134a) which potentially can drop significantly Mg GHG emissions [10].

Composites best environmental performance reported by Tempelman [9] are strongly dependent on EoL assumption (composite waste incineration). Though, other studies pointed out that, composites' EoL is a critical stage, due to its insignificant recycling rates: less than 1% [7], which does not offset their energy and GHG emissions reduction achieved at the use-stage [6,7,12]. In addition, waste incineration in the EU context is not considered the preferred option (importance of waste streams to trigger a circular economy). Though, some composites types can use secondary materials (valorization of waste streams that can be recovered to recycling) which is likely to decrease its embodied impact and reinforce their environmental applicability as a lightweight material.

A deeper conclusion was uncovered when a fleet-based approach was considered [13], lightweight vehicles measure can reduce environmental impacts in the near future but are not enough to achieve sustainable targets at a large scale and expected rates. In addition, Ehrenberger [10] highlighted that general conclusions on the comparison of lightweight materials cannot be drawn without ambiguity. A critical factor affecting LCA results is the vehicle useful lifetime (driven distance). The GHG break-even distance, i.e. the distance from which a lightweight material offsets its additional embodied burdens, is both influenced by material substitution ratios and fuel economy (powertrain) [6]. The GHG break-even distance was assessed by some studies [6–8,10,14] and controversial results were achieved, some studies reported minimum breakeven distances for Al [8] and others for A/HSS [14]. Without a sensitivity analysis, some studies showed only a "snapshot" of the results associated with the driving distance assumed. However, most studies included a sensitivity analysis for other parameters. Tempelman [9] found out that overall impact results were sensitive to changes in fuel economy but not to recycling rates and EoL scenarios. In contrast, some authors reported that results were critically dependent on the EoL scenarios (whether scrap can be utilized instead of primary material) and on the source of primary metal [10,12,14]. Another issue that brought additional ambiguity to the impact results achieved was the secondary mass reductions. Lightweight chassis and BIW components allow downsizing of secondary components (e.g. powertrain) which can represent 35 to 41% of the total mass reduction [1]. The accurate benefit of lightweight materials was not assessed in some studies since secondary vehicle mass reductions were neglected.

Due to the above mention key-parameters used (e.g. fuel economy, primary and secondary mass reduction rates, recycling rates, useful lifetime, and EoL scenarios) and different functional units chosen, direct comparison among studies can be challenging. Different authors simplified their inventory data by overusing assumptions, and neither all of them performed sensitivity and/ or uncertainty analysis (influence of key-parameters in the results). This source of variability is the major factor behind the controversial results, depending on the values assumed impact results and GHG break-even driving distance changed and consequently, the identification of the lightweight material with the lowest environmental impacts switched. Nonetheless, by performing a critical analysis of the discussed topics, the authors identify A/HSS as potentially the most preferable lightweight material, followed by Al, and Mg and composites as the less preferable.

4. Recommendations

Regarding the literature review, it is the authors' opinion that further improvements in LCA lightweight vehicle studies are needed. To formulate sound conclusions, better production inventories, use-stage key-parameters and EoL scenarios should be provided. In addition, sensitivity analysis should be performed for the key-parameters (including identification of the GHG break-even driving distance) and quantification of the overall uncertainty associated with LCI data should be disclosed. Moreover, other environmental impact categories beyond GHG emissions and energy consumption should be considered, to unveil other hotspots for improvements. Simultaneously, a more comprehensive understanding of the environmental performance of each lightweight material could be achieved if fleet-based system dynamics is considered, i.e. inclusion of temporal variations, through a Consequential LCA (C-LCA) approach. In addition, to account for the accurate benefit of lightweight materials secondary vehicle mass reductions should be considered.

When the above-mentioned recommendations are implemented it will be helpful to integrate the environmental results with economic data, to assess and improve the ecoefficiency of lightweight materials, thus tackling in a broader scope their sustainability. Lastly, if lightweight materials overall reductions are up to 10% [12], to achieve sustainability targets at a large scale and at expected rates, a more holistic intervention is needed, e.g. intersection of lightweight materials with hybrid vehicles and electrification (besides combustion vehicles: typically lightweight materials are pointed out as more useful in vehicles with more burdens in use-stage) and carsharing.

5. Conclusion

This study reviewed LCA studies mainly focused on lightweight materials (A/HSS, Al, Mg and Composites) for automotive chassis and BIW components to identify the materials with the lowest environmental impacts, trends and improvement opportunities. Since most impacts are associated with the vehicle use-stage (due to fossil fuel consumption), lightweight materials have environmental benefits in a cradle-to-grave approach. By performing a critical analysis, A/HSS is identified as the most preferable lightweight material, followed by Al. A/HSS was referred to as presenting higher recycling rates and Al with higher mass reduction rates. Mg production was mentioned as having environmental burdens associated with high GHG emissions (use of SF6 as cover gas) and composites with near-zero recycling rates at EoL.

The rates of mass reduction and recycling (at the production stage and EoL) were identified as crucial hotspots for the aimed environmental benefits of lightweight vehicles. Overall impact results were sensitive to changes in EoL scenarios and in the source of primary lightweight material (whether scrap can be utilized instead of primary material). At the use-stage, fuel economy, vehicle and powertrain type, and driven distance are among the most common factors contributing to GHG emissions. Different authors assumed different assumptions and key-parameters for critical hotspots. These studies show that the overall conclusions of LCA studies should not be generalized to different vehicles models (and components), since each model may have distinct key-parameters. Therefore, to support the decision at the design stage dedicated LCAs should be used with the integration of specific vehicle key-parameters.

To formulate sound conclusions, the authors recommended that, inventory data on production, use-stage and EoL should be clearer, GHG break-even driving distance disclosed, and uncertainty and/or sensitivity analysis are recommended. Other impact categories than GHG emissions and energy consumption should be considered to unveil other hotspots for improvements and when substantial technology change is assumed, C-LCA should be used to assess the predictive market uptake. In addition, to account for the accurate benefit of lightweight materials secondary vehicle mass reductions should be considered.

Lastly, it also will be helpful to integrate the environmental results with economic data, to assess and improve the ecoefficiency of lightweight materials, thus tackling in a broader scope their sustainability.

CRediT authorship contribution statement

Margarida Gonçalves: Conceptualization, Project administration, Investigation, Writing – original draft. **Helena Monteiro:** Writing – review & editing. **Muriel Iten:** Writing – review & editing.

Declaration of competing interest

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