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Life cycle energy of vehicles on lightweighting and alternative powertrain strategies—A review

Helena Monteiro[a,*], Rita Alonso[b], Margarida Gonçalves[c], Muriel Iten[a], Nídia S. Caetano[b,d,e]

[a] *Low Carbon & Resource Efficiency, R&Di, Instituto de Soldadura e Qualidade, 4415-491 Grijó, Portugal*
[b] *CIETI/ISEP – Centre of Innovation on Engineering and Industrial Technology/IPP-ISEP, School of Engineering, 4249-015 Porto, Portugal*
[c] *Low Carbon & Resource Efficiency, R&Di, Instituto de Soldadura e Qualidade, 2740-120 Porto Salvo, Portugal*
[d] *LEPABE - Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto (FEUP), 4200-465 Porto, Portugal*
[e] *ALiCE - Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

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Abstract

To improve vehicles environmental performance, different strategies have been explored namely to reduce the use stage energy. In order to avoid problem shifting, a life cycle perspective should be used to compare alternative solutions. This paper aims to compare existing studies focused on life cycle energy (LCE) of vehicles to analyze the impacts and benefits regarding two trending improvement strategies: lightweight materials and alternative powertrain selection. A Literature review was performed to systematize quantitatively the LCE results of different studies (e.g. presented among figures, tables, and literature text). The LCE results were compiled and normalized for the same driving distance, 200 000 km, per life cycle stage. Moreover, the study discusses research findings on the application of the two strategies to improve overall vehicles' LCE. As lightweight materials have generally higher embodied energy, the material selection is highly influenced by end-of-life scenarios. It was observed that carbon/glass fiber composites generally have the highest embodied energy, being a preferable option for vehicles that last longer driving distances. Innovative powertrains sourced by renewable energy sources, electric mixes, can significantly reduce vehicles' LCE use stage, counteracting the benefit of lightweight design. Thus, the benefit of both strategies should be studied together.

Abbreviations: AHSS, Advanced high strengh steel; Al, Aluminum; BAU, Business-as-usual; BEV, Battery electric vehicle; BiW, Body-in-White; BtL, Biomass to liquid; CFRP, Carbon fiber reinforced polymer; EoL, End-of-life; EU, European Union; FCEV, Fuel cell battery vehicle; FU, Functional unit; GFRP, Glass fiber reinforced polymer; HEV, Hybrid electric vehicle; HSCF, High Strength Carbon Fiber; HSS, High strength steel; ICEV, Internal combustion engine vehicle; LC, Life cycle; LCA, Life cycle assessment; LCE, Life cycle primary energy; Mg, Magnesium; PET, Polyethylene terephthalate; PHEV, Plug-in hybrid electric vehicle; TWDCI, Thin-wall ductile cast iron; PHFCEV, Plug-in hybrid fuel cell-battery vehicle

[*] Corresponding author.

E-mail addresses: himonteiro@isq.pt, himonteiro.rdi@gmail.com (H. Monteiro).

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1. Introduction

The transport sector is responsible for around 25% of carbon dioxide (CO_2) emissions in European Union (EU), and road transport represents more than 70% of those emissions. To achieve the EU climate neutral targets by 2050, the transport manufacturers need to decrease its emissions, through energy efficiency improvements, low-emission energy sources, improved design, material selection, and end-of-life (EoL) management. In fact, regarding the energy requirements, the use stage of a motorized vehicle is the most demanding stage, and generally measures to improve efficiency in this stage can result in significant benefits. Despite the broad scope of potential improvement measures applicable to this sector, there are currently two trending strategies to reduce energy consumption and CO_2 emissions of a vehicle's use phase: (a) to produce lightweight vehicles, through lightweight parts and new materials and (b) and to develop and test alternative vehicle powertrains.

Robust measures to improve a vehicle energy consumption should be analyzed based on a life cycle perspective. The comparison of alternative strategies based on Life Cycle Assessment (LCA) allows a more comprehensive account of the overall environmental benefit (or impact) of each strategy, avoiding problem-shifting (e.g. energy saved in use stage, end up being spent in manufacturing stage). LCA is a standardized methodology (ISO 14040/ISO 14044) that tracks the potential environmental impact of a product or system along its lifetime or part of it. It is often used to compare functional equivalent product alternatives and support decision. A wide range of life cycle environmental impact assessment methods and categories are available, among which the cumulative energy demand, which is a widely accepted category that accounts for the life cycle primary energy (LCE) in MJ.

Vehicles incorporate different materials and components, which directly affect its total weight. For the greater part of vehicle types, currently, iron and steel are the most used materials and these alone account for around 65% of a passenger vehicle weight [1]. Lightweight materials, indeed, are an effective strategy to reduce fuel consumption. For such, several LCA studies have analyzed the use of new alternative lightweight materials. Meanwhile, different powertrains (e.g., plug-in hybrid, hybrid, battery electric, fuel cell) are being developed with the goal of decreasing vehicles' fuel energy consumption, and studies focused on comparing their influence from a vehicles' life cycle perspective have emerged. In this context, studies have been applying LCA to study diverse automotive applications. LCA case studies, however, consider different, alternatives, system boundaries, lifetime driving distance, and EoL scenarios, not allowing a direct and clear comparison among studies. Furthermore, these results are quite often differently formatted, and disperse among text, figures, graphs, and tables.

To uniformize such results, this paper aims to compare existing LCA studies focused on LCE of vehicles, analyzing the main impacts and benefits regarding two trending improvement strategies: lightweight materials and alternative powertrain selection. This will allow readers to easily compare scenarios and their quantitative LCE results by life cycle (LC) stages. Lastly, the study synthesizes and discusses research findings on the application of these two strategies to improve overall vehicles' life cycle energy.

2. Methods

A search for recent literature published in the past 10 years was undertaken with the goal of selecting a sample of articles presenting LCE results documenting one of the two improvement strategies: (a) alternative materials to assess the effect of lightweighting; (b) alternative powertrains. Based on the available results, eight studies on lightweight materials were selected and analyzed. For each study, the LCE results for different material alternatives and their underpinning LCA assumptions have been identified and calculated (e.g., functional unit — FU, life-time mileage, vehicle type, powertrain, material alternative, part and vehicle weight, fuel consumption, and EoL scenario. For the alternative powertrain scenarios, LCE results were gathered from four studies. For each powertrain alternative, the underpinning LCA assumptions were identified, namely FU, vehicle's type and weight, powertrain, motor power, energy source, fuel and electric consumption and country. Overall, the LCE results were gathered from text, figures, graphs, and tables and systematized for different LC stages: material production, manufacturing, production, use stage, and EoL. To ease comparability, the LC results were computed for the same lifetime driving distance (200 000 km).

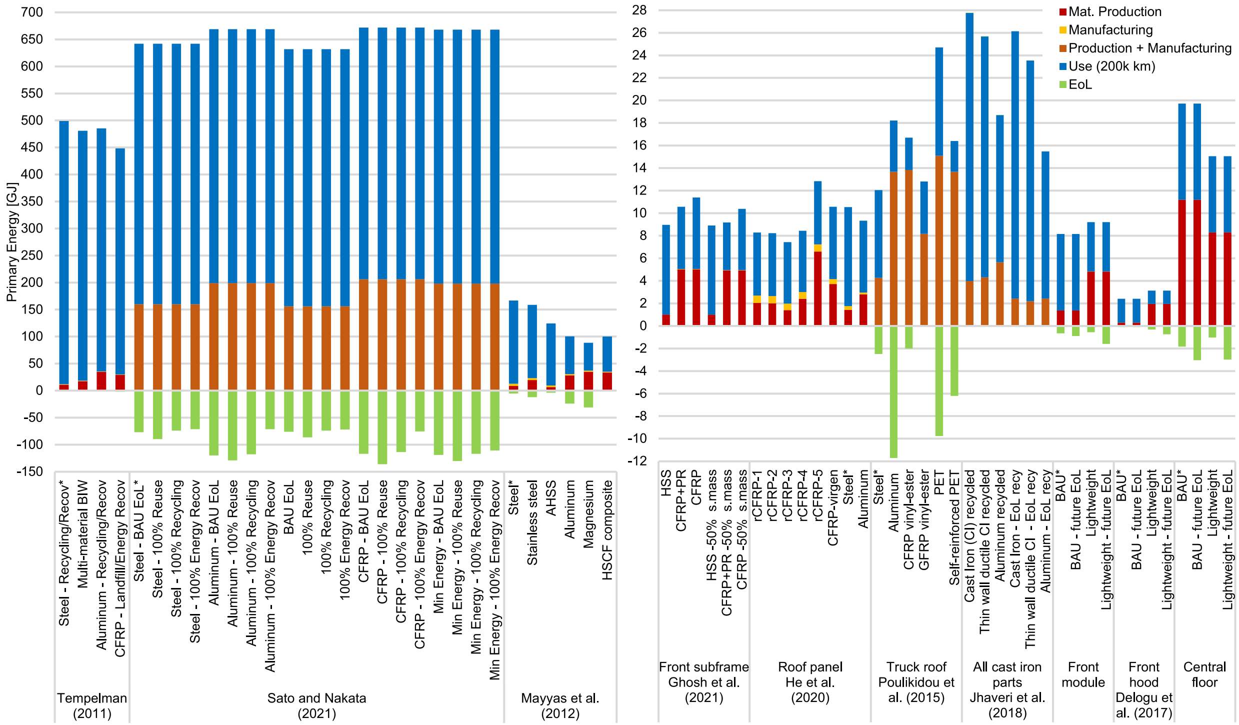

Fig. 1. Life cycle primary energy (GJ) of alternative lightweight materials for: (a) BiW, and (b) other smaller vehicle components.

3. Results and discussion

This section presents the main results of this literature review for the LC energy studies on lightweighting strategy (Section 3.1) and on alternative Powertrain or fuels (Section 3.2). The LC results are analyzed and compared to support the research findings towards the influence of the two strategies addressed.

3.1. Life cycle studies of lightweight strategy

The reviewed studies cover several lightweight alternatives for different components. LCE results (for 200 000 km) are presented in Fig. 1. It depicts studies focused on body-in-white (BiW) components of passenger vehicles (Fig. 1a) and on smaller automotive parts (Fig. 1b).

For a conventional BiW made of a steel including 45% High strength steel (HSS), Tempelman [2] analyzed three lightweight material alternatives for a compact diesel vehicle (6.9 L/ 100 km): (i) a multi-material, composed by 70% HSS, 20% aluminum (Al), 10% glass fiber reinforced polymers (GFRP); (ii) Al; (iii) Carbon fiber reinforced polymers (CFRP). The benefits of secondary weight reduction were also considered. Regarding the EoL, 99% of steel and 78% of Al were recycled (the remainder was landfilled) and energy recovery was considered for the GFRP. Production energy is provided for the BiW while operational energy is given for the full vehicle. Results showed the Al's BiW, had 3 times more the embodied energy of the conventional BiW, nevertheless it reduced part weight by 28%, and vehicle weight by 13%, which resulted in a 7.7% energy savings during use stage (200 000 km), and in an LCE reduction of 3.3%. Overall, in a LC perspective, the Al alternative was not better than the multi-material. The best scenario was the CFRP, that had a 2.5 times higher embodied energy than conventional BiW, but reduced part and vehicle weight by 52% and 23.5%, and resulted in 14% energy savings at use stage, and in a total LCE reduction of 9.5%.

Sato and Nakata [1] also studied four material alternatives for a passenger vehicle's BiW conventionally made of steel components (436 kg): Advanced HSS (AHSS) (342 kg), Al (271 kg), CFRP (217 kg), and material with minimum energy (271 kg Al, 4 kg AHSS; 4 kg CFRP). For each material scenario, four theoretical EoL scenarios were considered: the business-as-usual (BAU) recycling, 100% parts reuse, 100% material recycling and 100% energy recovery. LC results are presented for full vehicle production, use phase and EoL. EoL had a positive effect in all scenarios (resulting in primary energy credits). Results showed that both Al and CFRP have 24% and 29% higher embodied energy than the conventional alternative, respectively. Despite use stage represented around 69%–75% of LCE (disregarding EoL influence), the authors argued that the material selection must consider the entire LC, including the EoL, since reuse, recycling, and energy valorization have the potential to significantly reduce (partially offset) the material production impact. Assuming that BiW part can be reused, CFRP is the alternative with lowest LCE. Whereas if considering 100% recycling, the material alternative with minimum energy had the lowest LCE, followed by Al alternative.

Mayyas et al. [3] has observed that material selection for a BiW is a sensitive process influenced by the driving distance, the embodied energy in materials selected, and the EoL scenario assumed. Six material alternatives were considered: (i) conventional Steel, (ii) Stainless steel, (iii) AHSS, (iv) Al, (v) Magnesium (Mg) and (vi) High Strength Carbon Fiber/epoxy (HSCF). LCE results were provided for the production (material production and part manufacturing), use stage and EoL of the BiW component. For a 200 000 km driving distance, the alternative with lowest LCE was the Mg (which reduced by 47% the overall LCE associated with the conventional BiW, even without EoL credits), followed by the Al (with a 40% LCE reduction). And, if 95% recycling of these materials is considered, these two alternatives were even more favorable.

Moreover, Ghosh et al. [4] assessed the influence of using CFRP to replace HSS in a front subframe part of a Ford Fusion vehicle. The primary data for CFRP industrial production was provided and six alternatives have been considered: (i) HSS part (26.3 kg), (ii) CFRP part (18.9 kg), (iii) CFRP part and a consequent powertrain resizing (CFRP+PR), (iv) to (vi) previous alternatives (i) to (iii),respectively, with 50% secondary mass reduction. The results showed that, the CFRP part with no powertrain resizing or secondary weigh reduction, had 27% higher LCE than the HSS. Even assuming a powertrain resizing and secondary weigh reduction, for 200 000 km lifetime, the CFRP only achieved a marginal benefit (0.5% lower LCE than HSS). Ghosh et al. [4] identified two key aspects to lower CFRP environmental impact: (1) make use of recycled carbon fibers in CFRP and; (2) extend the vehicle lifetime (driving distance).

Furthermore, He et al. [5] studied eight roof panel alternatives for a gasoline powertrain of a Ford Fusion vehicle (9.1 L/ 100 km): (i) virgin CRFP, (ii) hot dip galvanized steel, (iii) Al, and five solution: (iv) to (viii) recycled CFRP (rCFRP) with alternative recycling methods. Results showed that, by using pyrolysis to produce recycled carbon fibers without shredding (rCFRP-3), the embodied energy of material production is 2.8% and 53% lower than the steel and Al panel's, respectively. However, by adding the part manufacturing energy, this benefit is offset. Poulikidou et al. [6] also compared six alternative materials for a roof panel, but in this case for a truck (with 40 ton): (i) Steel (grade DP800), (ii) Al (grade Al6061), (iii) CFRP, (iv) GFRP, (v) polyethylene terephthalate (PET), and (vi) self-reinforced PET (SrPET). In the study, the driving distance was assumed as 1 million km. The Al was found to reduce component LCE by 39% when compared to steel, being followed by CFRP (with a 35% LCE reduction vs steel). Nevertheless, when considering a 200 000 km driving distance, only the Al performed better than the steel alternative (with a 32% improvement). Given their embodied energy, all the composite materials performed worse. In fact, Al only performed better than steel due to EoL recycling credits (which offset its embodied energy).

Additionally, Jhaveri et al. [7] assessed LCE of using thin-wall ductile cast iron (TWDCI) in vehicle applications compared to conventional cast iron and Al. The material substitution for all cast iron components was assumed. For use stage, only the component mass-induce LCE is presented. Two alternative allocation approaches were considered: (i) the recycled content or cut-off approach, in which material scraps are free from environmental impacts, but no credits are given to the system for EoL material recycling or energy valorization; (ii) the avoided burdens or EoL recycling approach, in which the system is credited the benefits of material recycling at EoL (avoided burdens of virgin material production) or energy recovery. It was observed that both TWDCI and Al alternatives reduced overall LCE by 7% and 27%, respectively, when compared to conventional cast iron. The avoided burden approach had even lower LCE (reduction of 10 and 34% for TWDCI and Al, respectively).

Unlike the other studies, Delogu et al. [8], assessed innovative hybrid composites as a lightweight strategy for different parts of an electric passenger vehicle, instead of a ICE vehicle. For each part, two alternatives were studied: (i) a conventional (steel), and (ii) multi-material lightweight (e.g. Al, CFRP, GFRP). Generally, the lightweight alternatives reduced steel content, achieving a weight reduction of 34%, 42% and 21% for the front module, front hood, and central floor, respectively. Two EoL scenarios were considered: the BAU and a future improved one

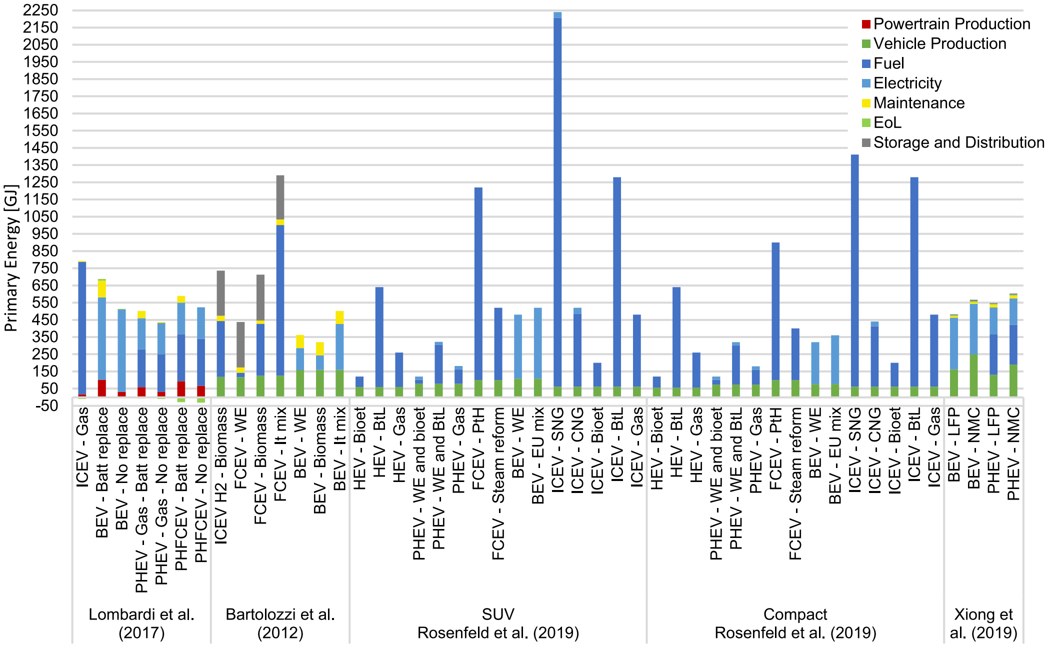

Fig. 2. Life cycle primary energy (GJ) of vehicles with alternative powertrains.

(with advanced post-shredding recycling). For a 150 000 km driving distance, the author concluded that the hybrid composite material parts had a higher LCE than conventional ones. Likewise, LC results for 200 000 km show that only one hybrid material part (central floor) was preferable to the conventional solution. Assuming a better EoL scenario (with increased recycling) benefits all solutions, and it may be even a more beneficial strategy than lightweighting for electric vehicles.

3.2. LC studies on alternative powertrain or fuels

The LCE results for the alternative powertrains and energy source scenarios are presented in Fig. 2.

Lombardi et al. [9] assessed a mid-size car (1700–1500 kg) with four powertrains: (i) internal combustion engine vehicle (ICEV) fueled by gasoline with a 104 kW; (ii) battery electric vehicle (BEV) with 75 W motor; (iii) plug-in hybrid gasoline-electric vehicle (PHEV); (iv) and a plug-in hybrid fuel cell-battery vehicle (PHFCEV). The LCE for production and EoL stages were given only for the powertrain, while use stage considered the full vehicle. Two scenarios were considered: with and without battery replacement during the lifetime. The study shows that all innovative powertrains perform better than the conventional ICEV. The best alternative was the PHEV with no battery replacement, followed by PHFCEV, and BEV, which reduced LCE by 45%, 37% and 34%, respectively. Nevertheless, if battery replacement is required, the benefit of these powertrains was significantly decreased (e.g., BEV had only a 12% LCE reduction vs. ICEV) because the embodied energy of battery production triples.

Bartolozzi et al. [10] evaluated seven alternatives for an urban commercial vehicle: fuel cell-battery vehicles (FCEVs) powered by (i) hydrogen either produced by wind electricity, (ii) biomass gasification electricity or (iii) the Italian electricity mix, (iv) ICEV powered by hydrogen (from biomass gasification), and BEV (34.2 kWh) using (v) electricity from wind generation, (vi) biomass gasification, or (vii) the Italian mix. The LCE results are only presented for non-renewable fossil energy. If hydrogen storage and distribution is accounted, the BEV powered by biomass electricity is the best scenario. Otherwise, the best scenario is the FCEV sourced by wind-hydrogen, which has a 46% lower LCE than BEV biomass electricity. The Italian electric mix presents itself as the worst option with, significatively higher LCE due to the fossil share in the electric mix.

Moreover, five different powertrain technologies, Hybrid electric vehicle (HEV), PHEV, BEV, FCEV and ICEV, were assessed by Rosenfeld et al. [11] for two vehicle types: SUV (1840 kg) and compact vehicle (1640 kg). Each of the powertrains was also sourced by different types of fuels. The best results were found for both the bioethanol HEV and the PHEV (sourced by wind electricity and bioethanol), which had a 75% lower LCE compared to the gasoline ICEV, for both vehicle types. Being partially gasoline fueled, the PHEV and HEV presented a 63% and 46% lower LCE than the ICEV. FCEV and BEV have a higher embodied energy (61% and 74% higher) than conventional ICEV. Bioethanol fuel can significantly reduce ICEV LCE by 58%. Options as synthetic natural gas (SNG), biomass to liquid (BtL) and power-to-hydrogen (FCEV PtH) are more energy-intensive than ICEV fueled by gasoline. Four powertrain scenarios were analyzed by Xiong et al. [12] for a compact vehicle, which included BEV and PHEV with two alternative batteries: Lithium iron phosphate (LFP) and Lithium nickel manganese cobalt oxide (NMC). The overall results showed that BEVs consumes less energy than PHEVs and, also, NMC powered vehicles entail higher LCE comparatively to LFP ones. Therefore, BEV LFP is the best scenario, followed by PHEV LFP.

4. Conclusion

This work presents an uniformized review of LCE studies focused on two trending strategies to reduce vehicles energy consumption: alternative lightweight material and powertrain selection. Overall, the authors conclude that both strategies have the potential to reduce the LCE of the reference scenarios (i.e. steel in the lightweight strategy and ICEV in the powertrain).

The results show that lightweight materials (Al, CFRP, GFRP, Mg) generally have higher embodied energy than conventional ones, even though most studies for passenger vehicle with conventional powertrain (ICEV) show that lightweighting is a worthwhile strategy to reduce vehicles LCE for a 200 000 km driving distance. Nevertheless, lightweight material selection is highly influenced by the EoL stage. Depending on the EoL scenario, the preferable lightweight material may change. Results showed that improvements in material recovery and recycling technologies of Al, Mg and composites could promote an offset of their production impact (through avoided burdens). Given that, lightweight materials with high embodied energy (e.g. CFRP/GFRP) are generally more advantageous for longer driving distance vehicles (e.g. trucks) and should see future improvements through the incorporation of recycled materials in their production process. In this way, lightweight material selection should be related with feasible disassembly, material recovery, and recycling strategies for future EoL. The development of better EoL scenarios may be more beneficial than lightweighting, specially for electric vehicles. Additionally, the allocation approach at EoL may also influence the results: the avoided burdens approach may discourage the use of secondary materials in cradle-to-gate studies and result in higher break-even driving distances. Instead, in a cradle-to-grave boundary it gets benefits (credits) for recycling, since the recycled materials at EoL are assumed to be equivalent to virgin ones, even though, the system studied may not use recycled materials at production stage.

Vehicles with innovative powertrains (BEV, FCEV) sourced by renewable energy sources (or electric mixes), can highly reduce use stage LCE when compared to ICEV. Thus, the embodied energy of alternative lightweight solutions for electric vehicles should always be considered to avoid problem-shifting, since an increase in embodied impact may not be offset by mass-induced energy savings at use stage. Studies in general conclude that innovative powertrains perform better than the conventional ICEV. However, if fossil primary energy is used to source BEVs and, FCEVs (e.g., fossil share in the regional electric mix; BtL; SNG; or other fossil fuel-based) these powertrains may end up having higher LCE. To complete, hot-spots for improvements are identified regarding the lightweight materials' EoL stage and powertrains' energy sources. Thus, both strategies should be studied together through a life cycle perspective and including EoL.

CRediT authorship contribution statement

Helena Monteiro: Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Rita Alonso:** Investigation, Formal analysis, Writing – original draft. **Margarida Gonçalves:** Supervision, Writing – review & editing. **Muriel Iten:** Writing – review & editing. **Nídia S. Caetano:** Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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