Life-cycle assessment of material and end-of-life scenarios for passenger cars

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Abstract

Having in mind the preponderance of the transport sector in the energy consumption and emission of pollutants, this study proposes to evaluate the environmental impacts of alternative scenarios in the introduction of alternative materials for lightweighting and to quantify the respective environmental impacts for conventional and alternative passenger vehicles, considering different alternative scenarios: weight reduction; material substitution of the glider; change of battery chemistry in electric vehicles and different end-of-life scenarios and energy mixes.

The glider's conventional materials were replaced by lightweight materials, such as aluminium and carbon fiber, reaching weight reductions from 30% to 40%. For the electric vehicles, it was also considered the replacement of the electrochemical type of the battery, from LMO to NMC622 and NMC811. When it comes to the energy mix, it was considered the current value in Portugal for the foreseen value of 2050, according to the Roadmap for Carbon Neutrality 2050, obtaining in-use energy savings of up to 70%. The software used to perform the LCA was Simapro and the database Ecoinvent.

The scenario that had the best performance in terms of climate change corresponds to the lightweighting scenario through the use of carbon fiber, originating a decrease of up to 32% on in-use energy and up to 44% on fuel consumption, representing on average, 58% of the environmental impacts in EVs and 81% in ICEVs. It was also concluded that, for EVs, it's crucial to implement reuse in batteries, as up to 166% of climate change impacts can be mitigated.

Keywords: Life-Cycle Assessment, Sustainability, Lightweighting, Electric Vehicles.

1. Introduction

In 2018, Europe (EU-28) had a final energy consumption of around 1124 Mtoe where 37% were oil products [1]. The transport sector was the most demanding, accounting for 33.9% of the final energy consumption [1]. Road transport is, by far, the most demanding in terms of final energy consumption, representing 80.4%, while the second most demanding transport mode, international aviation, accounted for 13.9% [1]. Diesel represented 55.1% of the energy use in road transport, followed by gasoline, accounting for 20.4% [1]. The latest data, from 2017, shows that, in that year, passenger cars accounted for 56.1% of the energy consumption in road transport, followed by trucks and light duty vehicles (39.2%) [1].

According to the European Environment Agency (EEA), in the EU-28, in 2018, the transport sector was responsible for 13% of the emission of particulate matter, the most harmful to human health, 11% of which due to road transport [2]. The transport sector emitted about 47% of NO_x, 39% due to road transport [2]. EEA's latest report on GHG emissions [3] states that the EU-28 plus Iceland produced, in 2018, a total of 4234 MtCO_2eq [3]. The transport sector was responsible for the emission of 946.9 MtCO_2eq, 21.9% of the total GHG emissions [3]. Road transport is responsible for around 93.6% of the transport GHG emissions.

This set the tone for the relevance of this study, as it's imperative that the automotive industry creates changes that lead to a reduction on such consumption and pollutant emission.

1.1. Legislative Framework

In order to do so, policies are being applied at a world, European and country-level. The most relevant worldwide directive is the Paris Agreement, a part of the United Nations Framework Convention for Climate Change (UNFCCC), the result of the COP21 [4].

At the European level, the White Paper, released in 2011 presents 40 concrete initiatives to increase mobility and several key goals by 2050 such as cutting carbon emissions by 60%, no more conventionally-fuelled cars in cities, 40% use of sustainable low carbon fuels in aviation and at least 40% cut in shipping emission and 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport [5]. The European Green Deal, released in 2020, states a set of measures to make Europe climate neutral in 2050 and to further reduce net greenhouse gas emissions by at least 55% by 2030 [6].

At the country level, Portugal's Sustainable Cities 2020 strategy, approved in July of 2015, aims to prompt local, regional and national officials to implement policies in order to make cities more prosper, more connected, healthier and fairer [7]. The approval of Decree-Law n.º 86-D/2016, in November of 2016, also emphasizes the need to promote environmentally sustainable policies and to reduce pollutants' emissions [4]. Portugal's Roadmap to Carbon Neutrality 2050 (RNC2050), submitted to the United Nations within the Scope of the Climate Change Summit, establishes the long-term strategy for carbon neutrality of the Portuguese economy by 2050, setting the path to carbon neutrality in a sustained manner [8].

1.2. Objectives

In this context, the goal of this study is to understand the potential environmental benefits of the use of alternative materials in a vehicle lightweighting perspective and is relevant for everyone involved in the transports sector. From manufacturers wanting to improve their vehicles' environmental performance to consumers who would like to make a more informed choice when buying a car, this study presents several alternative scenarios for vehicle lightweighting that translate into lower environmental impacts.

2. State of the Art

2.1. Improvement of environmental performance

The United States' Argonne National Laboratory has developed a vehicle-cycle module for the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, which evaluates the energy and emission effects associated with vehicle material recovery and production, vehicle component manufacturing, vehicle assembly, and vehicle disposal/recycling [9]. The latest version of the Series 2 GREET vehicle-cycle model includes three different vehicle types, five different types of propulsion and a vast variety of data sources in order to include a more inclusive characterization of the vehicle systems [10]. A collaborative Research & Development co-funded by the European Commission, the SUPERLIGHT-CAR, reported the benefits in terms of weight saving of using cast and wrought aluminium in various chassis' parts [11]. Raugei *et al.* [12] presented an LCA-based comparison of a range of lightweighting options for compact passenger vehicles, using advanced lightweight materials such as Al, Mg and carbon fibre composites. Mayyas *et al.* [13] implemented an LCA based design approach to assess the performance of vehicular Body-In-White's (BIW) through its complete life cycle, in order to aid in the early design stages, serving as an eco-design decision-making support tool. Delogu *et al.* [14] illustrates the combination of the LCA methodology with the traditional design procedure at two different levels of the component design phase, material choice and concept design, discussing the main barriers for modelling and integrating the environmental performances in the automotive concept design. Witik *et al.* [15] used an LCA and a manufacturing focused life-cycle costing to evaluate the potential advantages in automotive applications of several suitable lightweight polymer composites, which were later quantified and compared against magnesium and steel for a representative component.

Regarding EoL studies, Tapper *et al.* [16] evaluated the LCA framework and its ability to accurately determine the benefits of closed-loop composite recycling, with the aim of aiding future material selection for recycled carbon fibre reinforced polymer (CRFP). Duval *et al.* [17] assessed financially and through an LCA the current and proposed recycling business operations of a Canadian automotive dismantling company, concluding that the proposed recycling network would reduce greenhouse gas emissions and energy requirements by nearly 50% but would result in an unprofitable value proposition for the company. Zhu *et al.* [18] analysed the timing, scale, and composition of U.S. aluminium automotive body sheet (ABS) scrap generated from the aluminium ABS intensive vehicles with the highest U.S. sales through a dynamic flow analysis (2015–2050).

2.2. Evaluation of a vehicle's environmental performance

In order to protect the environment and human health, it's essential to have coherent information at the consumer level about the environmental impacts of vehicles, as it can influence its choices and, therefore, influence technology development. Thus, environmental ranking methodologies have been developed and applied at a country level, ranking road vehicles by some specific environmental impacts. These methodologies are based on a life-cycle analysis, yielding different results according to the boundaries and damage categories considered. The **USA's Green Score** considers three life cycle stages: Fuel supply cycle (WTT); vehicle in-use tailpipe emissions (TTW); vehicle embodied emissions regarding vehicle manufacture, assembly and end-of-life treatment [19]. It accounts for all types of technologies, even though BEVs, PHEVs, HEVs and FCEVs use a slightly different embodied emissions model, accounting for the specific battery weight and composition and assesses emissions of CO_2, CH_4, N_2O, CO, hydrocarbons (HC), NO_x and PM_{10}. BE's Ecoscore considers a partial life-cycle: fuel supply cycle (WTW); vehicle in-use exhaust emissions (WTT+TTW) and assesses the emissions of CO_2, CH_4, N_2O, CO, HC, NO_x, PM_{10} and SO_2 [20]. Ecoscore allows the user to obtain results using the NEDC or the WLTP and can be applied to ICEV, BEV, HEV and PHEV technologies. Ecoscore uses weight indexing and external costing [20]. As for the UK's Next Green Car **UK's Next Green Car**, it assesses the same three life-cycle stages: fuel supply cycle (WTT); vehicle in-use tailpipe emissions (TTW) and vehicle embodied emissions regarding manufacturing and assembly, not accounting for the end-of-life treatment [21]. It can be applied to all conventional and alternative technologies, even though its database doesn't present any FCEVs and assesses the emissions of CO, NO_x, $NMOG$, PM_{10}, SO_2, CO_2, N_2O and CH_4, measured through the outdated NEDC. UK's NGC is based on weight indexing and environmental economics.

3. Methodology

Figure 1 presents the flowchart of the methodology used and the LCA phases considered in this study. This study uses the LCA as its main tool, mainly on a craddle-to-grave approach [22].

This methodology is based on an extensive literature review with the goal of developing solutions on the implementation of alternative scenarios for vehicle lightweighting of conventional and alternative powertrain technologies.

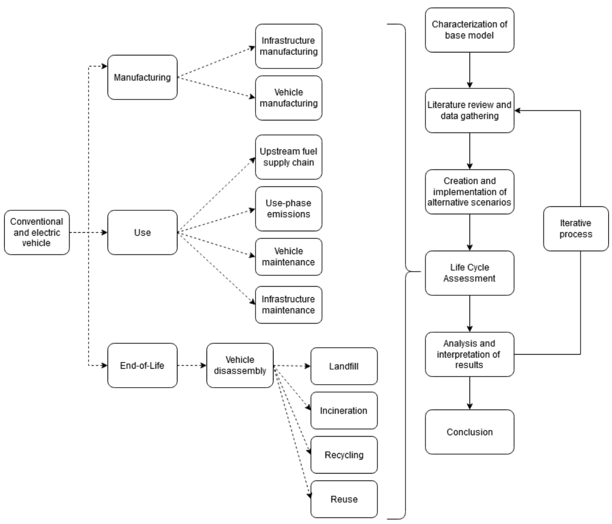

Figure 1: Methodology flowchart and LCA stages considered

The software used to model and perform the Life Cycle Analysis was SimaPro, the databases were provided by ecoinvent and the impact assessment was performed with ILCD 2011 Midpoint+ . The first step was to characterize both Simapro's conventional and electrical base vehicles in terms of materials and weight.

3.1. Case Study Description

3.1.1 Manufacturing

The baseline conventional vehicle considered was a small sized, Euro 4, petrol-powered with an engine of up to 1.4 liters and optimized for a vehicle of 1234 kg. SimaPro splits this vehicle in two modules: the glider and the internal combustion vehicle. The glider, weighting 913 kg, includes: the body of the car, the steering, braking and suspension system, tyres, cockpit equipment (seats, belts, etc.) and non propulsion related electronics. The internal combustion engine data, weighting 321 kg, is based on a Volkswagen Golf A4, a C-segment passenger car.

The electric vehicle (EV) has a weight of about 918 kg without battery and a 262 kg battery. The energy density of the battery was 114 Wh/kg, corresponding to about 120 km of driving range. The car and all its subassemblies (glider, powertrain and battery) had a life expectancy of 150.000 km. This data was obtained via Simapro's specifications. The glider, with the same proportional material composition of the ICEV's, weighted 838 kg, the powertrain 77 kg and the battery pack 262 kg.The powertrain, suitable for a system of about 100 kW maximum power, is split into five components: a 6.2 kg charger, a 4.5 kg converter, a 53 kg electric motor, a 9.5 kg inverter and a 3.9 kg power distribution unit. The battery is composed by the battery pack, containing 14 cells, the battery casing, the connectors and the power management unit. The battery pack, containing 14 single LMO cells, provides an electric power of 2.1 kWh and a voltage of 48 V. The battery cell refers to one single cell and is split into anode, battery separator, cathode and a share of other materials.

3.1.2 Use

For both the conventional and alternative vehicles, it was assumed that the vehicles achieve a total transport performance of 150,000 km which corresponds to approximately 10 years at an average annual use of 15,000 km. The use-phase parameters of baseline vehicles were not altered.

For the conventional vehicle, the fuel was considered to be low-sulphur petrol with a consumption of, according to Simapro's specifications, was 7.24L/100km. Vehicle maintenance was taken into account, consisting of the replacement and disposal of regular components and substances. Road infrastructure construction and maintenance also enter the use phase. Both road construction and maintenance refer to one meter and year (m*a), both being modelled as a constant renewal rather than as a one-time expenditure and end-of-life and was assumed to be the same for every vehicle and every scenario.

For the alternative vehicle, the energy was considered to be the current portuguese mixture, based on data from DGEG [23]. The in-use energy consumption, according to Simapro's specifications, was 26.02 kWh/100km. The remaining parameters in the use-phase of the alternative vehicle were considered to be the same as of the conventional's, apart from road maintenance, due to the lower amount of electric vehicles circulating, and, therefore, its lower impact on road maintenance.

3.1.3 End-of-Life

The end-of-life scenario for all components but the battery was considered to be landfill, incineration with energy recovery, recycling and disposal, with the share of each process depending on the material's family type. The end-of-life base scenario modelled on Simapro for all components but the battery on both types of base vehicles are based on reference studies. For the electric vehicle's battery, the end-of-life scenario consisted of hydrometallurgical and pyrometallurgical treatment, both with an equal share of 50% of the battery's weight.

3.2. Definition of Alternative Scenarios

The literature review suggests that the glider has the most potential for weight saving. Having that in mind, two main trends for lightweighting arise from the literature review. One more focused on maximizing the use of aluminium and another focused on a multi-material approach. The Al-intensive scenario, from now on known as Al Scenario, focuses on the intensive use of aluminium as a lightweight strategy, not accounting for reinforced polymers. This scenario was based on the study by [9], with some modifications. The multi-material scenario, from now on known as MM Scenario, uses a multi-material approach with the core of its weight saving being on CFRPs and GFRPs, as was based on [9] study. For both types of vehicles, two versions with a medium and high substitution of glider materials were simulated. The latter simulates a more conservative material substitution scenario, with smaller weight savings, and the former a more aggressive, with higher weight savings.

While the high substitution version of this scenario has no alterations to the original material shares, the medium substitution presents some weight reduction differences based on bibliographic reviews.

In both versions, the internal combustion engine didn't suffer any material substitution. For the EV, the powertrain systems (charger, converter, electric motor, inverter and power distribution unit) weren't taken into consideration for any material substitution. For the battery, however, three scenarios were firstly taken into account:

- Change of cathode chemistry
- Material substitution of the battery casing
- Increase of battery power, from 30 kWh to 60 kWh

Two different cathode chemistries were simulated in order to follow the current market trends and based on available literature.

- NMC622 - $Li(Ni_{0.6}Mn_{0.2}Co_{0.2})O_2$, with an energy density of 0.156 kWh/kg, a power of 41 kWh and a weight of 262 kg. All these parameters refer to the pack.
- NMC811 - $Li(Ni_{0.8}Mn_{0.1}Co_{0.1})O_2$, with an energy density of 0.170 kWh/kg, a power of 45 kWh and a weight of 262 kg. All these parameters refer to the pack.

The battery casing of the battery, weighting 30.4 kg of steel, was subjected to material substitution by aluminium, allowing for the saving of 66%. This replacement was made through the density and volume analysis. Structural and design considerations were not taken into account in this analysis.

The possibility of upgrading on both chemistries the battery power to a value similar to the current trends while maintaining the same energy densities, this case a power of 60 kWh, was studied but not taken into account.

3.2.1 High Substitution Version

The high version of both MM and Al scenarios are largely based on study [10]. While the MM scenario of this version presents almost no material change to the referred study, for the Al scenario, a literature review was conducted and several components suffered material changes, when compared to the MM scenario.

For the creation of the final MM and Al Scenarios and its integration of both MM and Al scenarios on Simapro, the total mass of each different material in each component and in each scenario was calculated and then compared with the weight of the same material in the base scenario. The weight reduction proportion of each material was mapped and then applied to the same material of the base scenario. A generic weight reduction equation, equation 1, follows.

$$m_{f,sc_j,i} = 1 - \frac{m_{st,conv,i} - m_{st,sc_j,i}}{m_{st,conv,i}} \times m_{SMP,conv,i} \quad (1)$$

Where $m_{f,sc}$ is the final mass of the material i in scenario j, $m_{st,conv}$ the mass of the material i in the conventional scenario of the study [10], $m_{st,sc_j,i}$ the mass of the material i in scenario j of the adaptation scenario of the study [10] and $m_{SMP,conv,i}$ the mass of the material i in the Simapro conventional model.

3.3. Medium Substitution Version

A literature review was conducted in order to implement more conservative material substitution shares. For both MM and Al scenarios, several components were reviewed and a more conservative approach was taken in their substitution.

3.4. Influence of weight on energy consumption

The decrease on in-use energy consumption consumption on both vehicles due to vehicle lightweighting was taken into consideration Based on study [24], it was assumed that the reduction on fuel consumption would follow a non-linear function, according to equation 2.

$$E_f = E_i(0,694 \times \frac{M_f}{M_i} + 0,2995) \qquad (2)$$

Where E_f is the final energy consumption after the weight reduction, E_i is the initial energy consumption before the weight reduction, M_f the final vehicle weight after the weight reduction and M_i the initial vehicle weight before the weight reduction.

3.5. Renewable Energy Sources Scenario

A renewable energy sources scenario, **Use-RES**, was modelled for both vehicle technologies to take into consideration the portuguese renewable energy intensive grid mixture for 2050, according to Portugal's Roadmap to Carbon Neutrality 2050, based on [23] and [8]. It was assumed that all use and end-of-life processes that included the use of electricity, including the use-phase electricity consumption for the alternative vehicle, had the mentioned mixture.

3.6. End-of-Life Scenarios

For the conventional vehicle, two end-of-life scenarios were considered, both considering that 100% of vehicle was disassembled and undergo a generic waste scenario. The difference between the base EoL scenario, **EoL-1** and the RES scenario, **EoL-RES**, lays in the electricity mixture used in all processes involved in the disassembly, recycling, landfill, disposal and incineration had the current portuguese mixture. EoL-1 considered the use of the current portuguese mixture and EoL-RES the 2050 renewable mixture.

For the EV, five end-of-life scenarios were simulated, with the battery recycling process was always consisting of 50% hydrometallurgical and 50% pyrometallurgical treatments processes, varying only the electricity mixture depending on the scenario. It was also assuming that remaining components, glider and powertrain, would always be submitted to the generic waste scenario. For all scenarios but the Use-RES, the EoL electricity mixture for all components was the current portuguese mixture.

The first scenario, designated by **EoL-0**, didn't consider any type of EoL treatment for the battery, assuming the whole of the battery would be disposed. The second scenario, the base EoL scenario, **EoL-1**, assumed that 100% of the battery would be recycled. The third scenario, **EoL-2**, assumed that 50% of the battery would be recycled and 50% of would be reused in the same type of use, but, on city cars. The third scenario, **EoL-3**, assumed that 70% of the battery would be recycled and 30% would be reused. The fourth scenario **EoL-4**, assumed that 90% of the battery would be recycled and 10% would be reused. The fifth scenario **EoL-5**, assumed the use of two batteries during the lifetime of the vehicle: the first one completing its whole life expectancy of 100,000 km on the vehicle and with an EoL scenario of 90% recycling and 10% reuse, and a second one completing only 50,000 km and with an EoL scenario of 70% recycling and 30% reuse. The modelling of this scenario consisted of considered 1.5 batteries on the vehicle life-phase and a weighted average for the recycling and reuse of the battery.

Finally, the Renewable Energy Sources Scenario, **Use-RES**, presented on subsection 3.5, takes into account the use of the 2050 portuguese mix in all end-of-life processes, including the battery. The EoL scenario for former component was assumed to be 100% recycling and 0% reuse.

4. Results and Discussion

4.1. Weight reduction

Table 1 presents the weight of the different materials for the base, MM and Al scenarios. Red cells represent a weight increase of the designated material on that scenario and green cells a weight decrease, compared to the base scenario.

As expected, the MM scenario presents the biggest weight savings, reducing the weight of the glider by around 63%. The Al scenario reduces the weight of the glider by 39%. The main weight saving for both MM and Al scenarios occur on the reduction of the steel share.

For the materials that represent a category, such as electronics, plastic and steel, the original proportion of materials present on the base scenario is kept.

4.1.1 Medium Substitution Version

These alterations yield the following material shares for the MM and Al scenario, presented in Table 2.

The medium substitution presents a 35% weight

Table 1: Glider material shares and weight variation for base, Al and MM scenarios, high substitution version. Red cells represent material's weight increase and green cells weight decrease, when compared to the base scenario.

Material	Base Scenario	Al Scenario	MM Scenario
	Weight [kg]	Weight [kg]	Weight [kg]
Cast Al	3,32	206,01	38,65
CFRP	-	-	9,11
Copper	5,90	5,90	5,90
Electronics	1,86	1,86	1,86
GFRP	0,37	0,37	0,37
Glass	27,88	27,88	17,78
Iron	-	17,54	10,10
Lead	2,07	2,07	2,07
Magnesium	0,59	7,44	7,44
Oil	2,64	2,64	2,64
Organic	15,33	14,38	14,09
Paint	10,22	10,22	5,11
Plastic	108,07	94,68	83,56
Rubber	39,36	39,06	38,26
Steel	693,26	112,69	94,65
Wrought Al	0,94	9,91	3,29
Zinc	1,19	1,19	1,19
Total	**913**	**553,8**	**336,1**

Table 2: Glider material shares and weight variation for base, Al and MM scenarios, medium substitution version. Red cells represent material's weight increase and green cells weight decrease, when compared to the base scenario.

Material	Base Scenario	Al Scenario	MM Scenario
	Weight [kg]	Weight [kg]	Weight [kg]
Cast Al	3,32	241.44	58.47
CFRP	-	-	8.35
Copper	5,90	5,90	5,90
Electronics	1,86	1.86	1,86
GFRP	0,37	0.37	0,37
Glass	27,88	27.88	17,78
Iron	-	17,07	9.27
Lead	2,07	2,07	2,07
Magnesium	0,59	7,44	7,44
Oil	2,64	2,64	2,64
Organic	15,33	14,38	14,09
Paint	10,22	10,22	5,11
Plastic	108,07	94,68	83,56
Rubber	39,36	39,06	38,26
Steel	693,26	112,69	94,65
Wrought Al	0,94	11.62	3,29
Zinc	1,19	1,19	1,19
Total	**913**	**590.5**	**354.3**

reduction for glider of the Al scenario and 61% for the glider of the MM scenario, compared to the base scenario. When compared to high version, the medium version for the Al scenario is 6% heavier and 5% for the MM scenario.

Table 3 presents a weight breakdown of the different scenarios per vehicle technology. As referred before, the ICEV's engine and the BEV's battery and powertrain weights remained unchanged.

Table 3: Weight breakdown of the different scenarios, for different vehicle technologies

		Glider [kg]	Vehicle [kg]
Petrol vehicle	**Base**	913,0	1234,0
	Al, Medium	590,5	911,5
	Al, High	553,8	874,8
	MM, Medium	354,3	675,3
	MM, High	336,1	657,1
Electric Vehicle	**Base**	838,0	1177,1
	Al, NMC622, Medium	537,8	876,9
	Al, NMC811, Medium	537,8	876,9
	Al, NMC622, High	504,3	843,3
	Al, NMC811, High	504,3	843,3
	MM, NMC622, Medium	320,4	659,5
	MM, NMC811, Medium	320,4	659,5
	MM, NMC622, High	303,9	643,0
	MM, NMC811, High	303,9	643,0

4.2. Impact assessment

For the upcoming scenario results, the impact category considered will be climate change as it's currently one of the most relevant and the one most often discussed by decision makers.

For the ICEV, the manufacturing phase contributes for climate change with 22%, the use-phase with 82% and the EoL with -5%. For the EV, the manufacturing phases contributes for climate change with 39%, the use-phase with 60% and the EoL with 2/The differences between the life-cycle shares of the different vehicles are mainly explained by ICEV's in-use emissions and the more demanding fuel upstream cycle. For the EoL, the EV's EoL positive contribution comes from the battery's energy intensive recycling process, which proponderance is particularly high due to its EoL assumed in this scenario - 100% of the battery's weight would be recycled, with no reuse whatsoever.

Figure 2 presents a comparison of lightweight scenarios for the climate change impact category and for the conventional vehicle.

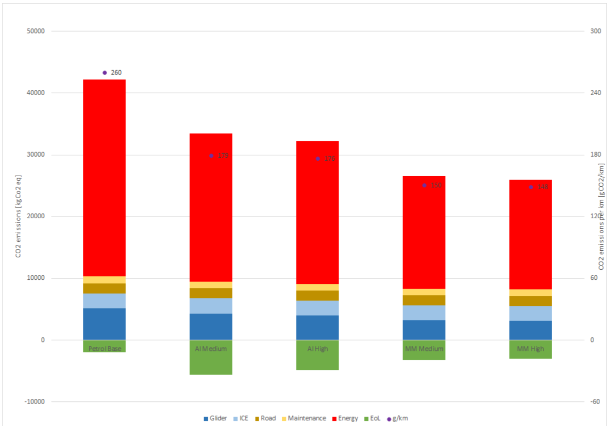

Figure 2: Petrol, scenario comparison, climate change

The scenario with the best environmental performance is the multi-material with the high substitution version. It presents an overall 32% reduction on climate change compared to the base scenario. This result can be explained due to this scenario presenting the highest weight saving potential and, therefore, also presenting the biggest fuel saving.

The use-phase, especially the fuel consumption, presents the biggest contribution to climate change in all scenarios, averaging 81%.

The trend of this vehicle typology is to diminish its climate change contribution with the reduction of vehicle weight. Both Al medium and high scenarios present the biggest EoL emission saving due to the preponderance of aluminium in the glider - 194% and 153% reduction potential respectively. Also, its high recycling potential is what makes the EoL negative mission contribution so big, enabling the total reduction of impacts to be 31 and 32%.

In the electric vehicle, however, the trend is not so clear, as Figure 3 shows.

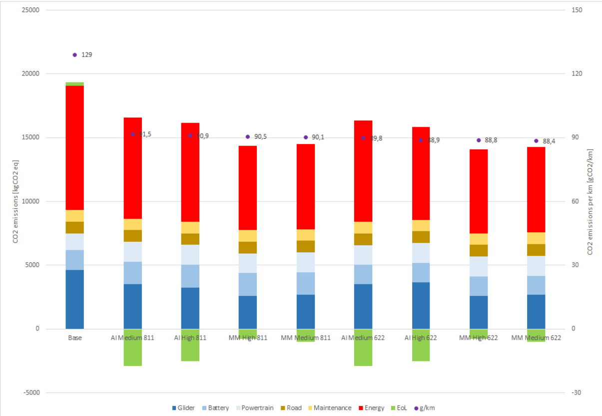

Figure 3: Electric, scenario comparison for 100% recycling and 0% reuse of battery, climate change

The scenario with the best environmental performance is the multi-material, but with the medium substitution version, even though it beats MM Medium version by only 0.3%. Even though the MM-High presents the biggest weight saving potential, of 48%, the amount of energy that gets put into the manufacturing and later disposal with no recycling potential, doesn't compensate in terms of emissions.

Following the conventional vehicle's trend, the use-phase, namely the fuel consumption, still presents the biggest climate change contribution, of 53% in average, even if by lesser margin than in the conventional's. This difference is expected do vary largely on the country's electricity mix.

Regarding the EoL, the base scenario is the only scenario where this stage accounts for a positive contribution. This happens due to the steel intensive glider, that has a lower recycling potential when compared to the aluminium's, also due to its weight being higher than the other scenarios, meaning that it has a higher material and energy demand, and because of the battery's contribution, as we're assuming the EoL-1 scenario (100% recycling for battery).

Figure 4 compares the EoL scenarios for the base petrol vehicle. In this scenario, the use of the renewable energy sources was considered in EoL processes. There's an increase of 8% on the negative contribution for climate change in the EoL-RES scenario, meaning that the use of mixture translates into a lower environmental impact than the conventional's.

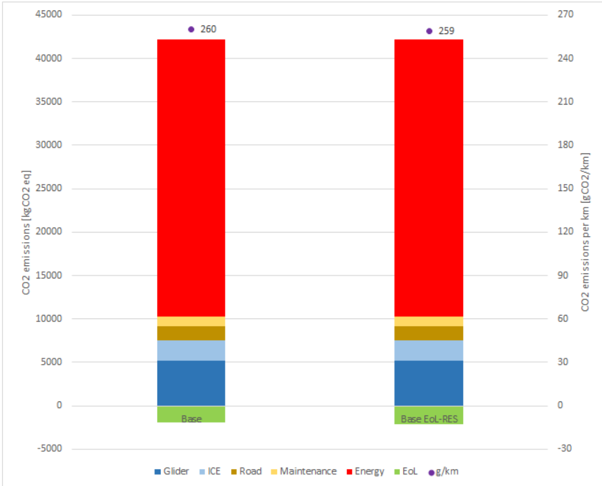

Figure 4: Petrol base, scenario comparison for the use of renewable sources in the EoL, climate change

Figure 5 compares the same EoL scenarios for the petrol vehicle scenario with the best environmental performing petrol, the MM High scenario.

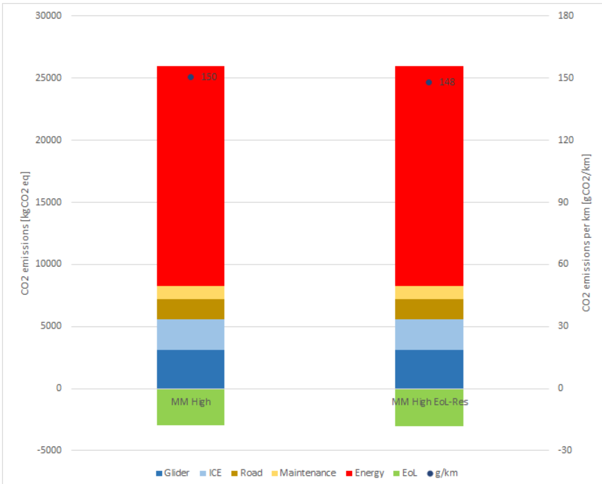

Figure 5: Petrol MM High, scenario comparison for the use of renewable sources in the EoL, climate change

The same conclusions as the former's apply to

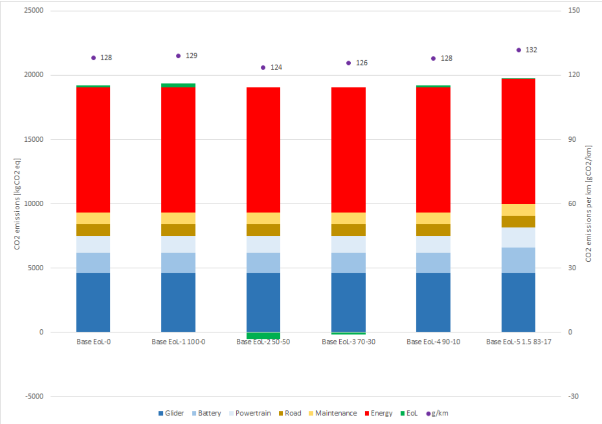

Figure 6: Electric base, EoL scenario comparison, climate change

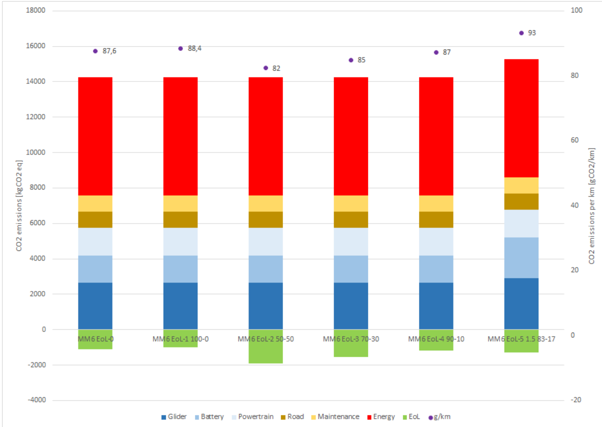

Figure 7: Electric MM Medium 622, EoL scenario comparison, climate change

this scenario, as there's a reduction on the climate change emissions for the EoL-RES secenario.

Figure 6 compares the six different EoL scenarios for the electric base vehicle. The effects of the EoL of the battery can be analysed by comparing scenarios EoL-0 and EoL-1 with the remaining. Figure 7 compares six scenarios, this time for the best environmental performing electric vehicle scenario, the MM Medium 622 scenario.

For the base scenario, the EoL is the the only stage that vary, due to the energy intensive recycling processes and the reuse (or lack of it) of the battery. Scenario EoL-1 presents a 166% larger positive climate change contribution than the the EoL-0, therefore confirming the energy-intensive recycling process of the battery. As it was expected, scenario EoL-2 is the one with the best environmental performance, with a 4% reduction, showing the preponderance of battery reuse in similar applications. When analysing scenarios EoL-1, EoL-2, EoL-3 and EoL-4, the trend is very obvious - the higher the share of the battery reuse, the smaller the EoL contribution for climate change of the vehicle. For EoL-5, it is possible to see the increase on the manufacturing stage due to the different battery consideration. Even though the weighted average of the battery's recycling and reuse share is located between the values of the scenarios EoL-3 and EoL-4, the reuse contribution is not high enough to compensate for the impacts of the battery's manufacturing material and energy demands, as the latter scenario still presents the highest CO_2 emissions per km.

Similar conclusions can be applied for the MM Medium 622 scenario. For both EoL-0 and EoL-1 scenarios, the former has a bigger climate change contribution, even if only 1%, due to the energy intensive recycling processes than the latter. The trend of lesser climate change impacts with higher battery reuse shares maintains, with the EoL-2 scenario performing the best, enabling a 7% reduction in g/km, compared to EoL-1.

Scenario EoL-5 is still the scenario with the highest climate change contribution, even though its EoL emissions are between EoL-3's and EoL-4's.

Figures 8 and 9 present a comparison for the implementation of renewable energy sources on the electric base and best performing vehicle's use and end-of-life stages, respectively, as described on Section 3.5.The EoL scenario considered for both vehicles and scenarios was EoL-1, where 100% of the battery weight is to be recycled.

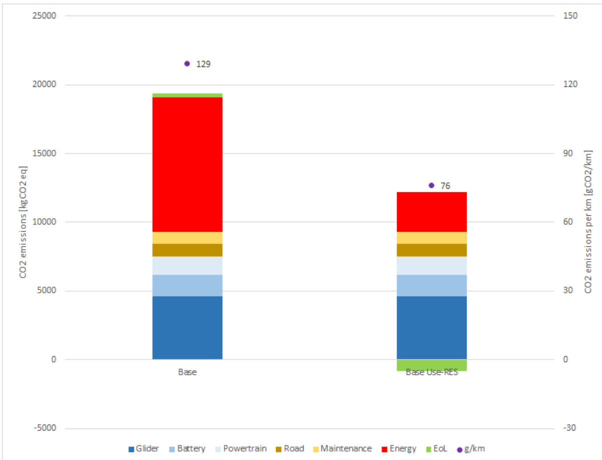

Figure 8: Electric base, scenario comparison for the use of renewable sources on use phase and EoL, climate change

The impacts of the electricity mixture are expressive leading to reduction of impacts of 41% and 43% in the base and MM Medium 622 respectively, as the use stage is dominant on both vehicles. The manufacturing stage contribution didn't suffer any change as the mixture remained the European

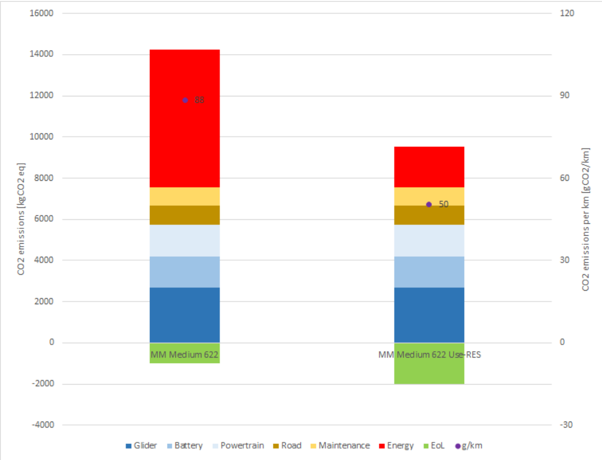

Figure 9: Electric MM Medium 622, scenario comparison for the use of renewable sources on use phase and EoL, climate change

one. The energy consumption, however decreased by 70% on both vehicles and the EoL contribution by 160% and by 99% on the base and MM Medium 622 vehicles, respectively. These results show the preponderance of fossil fuels on the current Portuguese mixture, which still account for approximately 43% of the total electricity production [23], and the importance of RNC2050 [8] and its reduction impact potential through the use of renewable energy sources.

5. Conclusion and Future Work

The goal of this study was to create sustainable vehicle lightweighting strategies for alternative and conventional passenger cars. For this implementation and modelling method, the integration of CFRP as a lightweight material presents the highest weight saving potential with lowest associated climate change contribution, independently of the vehicle technology. The development of this material's recycling industry is critical for its integration.

Even though this trend is more noticeable on electric vehicles, the manufacturing stage can't be ignored as it can be responsible for up to 51% of a vehicle's climate change contribution. This emphasizes the need to modify the current environmental validation guidelines to include the whole life-cycle, in opposition to accounting for the use stage only.

The energy consumption in the use stage is dominant in every scenario independently of the vehicle technology, making the changes in the electricity mix of particular importance for this sector, especially with the current European directives focused in phasing out combustion vehicles. The integration of the renewable energy mixture would translate in a 70% decrease on the energy consumption of both electric base and best performing scenario.

The reduction on energy consumption, consequence of the vehicle lightweighting, on both technologies, proved to be the main factor for to the decrease of environmental impacts. For the best performing petrol scenario, the multi-material approach with high material substitution, in-use energy consumption decreased by 44%, while for the best performing electric scenario, the MM High 622, the same in-use energy consumption decreased by 31%.

When it comes to batteries, the change of cathode chemistries from LMO to NMC622 or NMC811 presented a significant increase on available power - from 30 kWh to 41 and 46 kWh, respectively, there is no significant advantage to integrate NMC811 batteries instead of NMC622, as this study doesn't take into consideration battery downsizing. Significant impact reduction could derive from the lightweighting of the battery whilr it would still maintaining its capacity but at a lower energy density.

In terms of the end-of-life analysis, the main object of study was the electric vehicle, where the battery EoL proved to be critical. Depending on the recycling ans reuse shares, impact mitigation can increase from 18% up to 90%, depending on the recycling and reuse shares.

As a result of this study, it's expected that the trends for the future are more clear when it comes to vehicle lightweighting and alternative scenarios for the use of renewable energy sources and end-of-life scenarios.

Design considerations weren't taken into account in the present study. Further work can be done on the design feasibility of the substitution and implementation of lightweight materials on specific automotive components. It's also suggested to perform a financial analysis as the investment cost of the integration of lightweight materials may turn the project economically unfeasible. Furthermore, a deeper analysis to the end-of-life scenarios is advised, with special focus on the battery's. The battery reuse scenarios can be subjected to further work in order to take into consideration battery reuse in other applications, such as energy storage systems, which was not considered in this study.

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