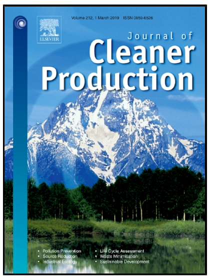

Life cycle energy use and greenhouse gas emission of lightweight vehicle – a body-in-white design

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Life cycle energy use and greenhouse gas emission of lightweight vehicle – a body-in-white design

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Abstract

A life cycle assessment (LCA) study is performed to compare the life cycle primary energy demand (PED) and global warming potential (GWP) of steel baseline automotive body-in-white (BIW) with three types of lightweight Scenarios. Scenario I, Scenario II, and Scenario III use advanced high strength steel (AHSS), aluminum alloy (Al alloy), and carbon fiber reinforced plastic (CFRP), respectively. China Automotive Life Cycle Database (CALCD), onsite data of Chinese automotive industry in 2015-2017 and process models are used for inventory analysis in this study.

The results indicate, among the different lightweight Scenarios for the BIW, the Scenario II provides the lowest PED and GWP during a lifetime travelling distance of 200,000 km. Scenario I shows the best break-even distance. Scenario III presents lower PED and GWP relative to the base case; however, it does not reach a breakeven for GWP within the lifespan of 200,000 km.

Sensitivity analysis results depict that a combination of longer lifetime distance, larger fuel consumption and smaller substitution ratio is beneficial for lightweight BIW Scenarios, especially for Scenario III, to achieve the largest PED and GWP reduction compared to the baseline in the full life cycle.

Keywords Body-in-white (BIW); Life cycle assessment; Lightweight design; Primary energy demand (PED); Global warming potential (GWP)

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1 Introduction

Nowadays, several approaches have been applied in the automotive industry to comply with increasingly stringent fuel consumption and exhaust gas emissions regulations, including powertrain efficiency improvement (Gao et al., 2015), rolling resistance reduction (Liu et al., 2011), electrification (Mayyas et al., 2017) and vehicle lightweighting (Helms and Lambrecht, 2007). Among these methods, vehicle lightweighting is viewed as an efficient solution for fuel economy improvement and emissions reduction (Cui et al., 2011). “New energy vehicles development strategy” shows that vehicle lightweighting development goals of 2020, 2025 and 2030 are 10%, 20% and 30% reduction of the total curb weight, respectively (TRESNEV Steering Commitee, 2016). Automotive bodies widely use lightweight materials ranging from conventional advanced high strength steel (AHSS), magnesium alloy, aluminum alloy (Al alloy), and, more recently, carbon fiber reinforced plastic (CFRP). Al alloy and CFRP, which offer large potential for weight reduction while maintaining the same stiffness and strength as steel, are the most promising lightweight materials of body-in-white (BIW) in the near future (TRESNEV Steering Commitee, 2016). The weight proportion targets of Al alloy and CFRP are expected to be 30% and 5% of the total curb weight by 2030, respectively (TRESNEV Steering Commitee, 2016). CFRP may provide up to 10% reduction of the overall weight of a vehicle, as it can be 35% and 60% lighter than Al alloy and steel, respectively (Das, 2011).

From the life cycle perceptive, lightweight materials generate larger environmental impacts on a weight basis than conventional steel primary due to energy-intensive manufacture and end-of-life (EoL) treatment stages (Witik et al., 2011a). In specific, CFRP is reported to consume 5-20 times of more energy and generates 8-30 times of more carbon dioxide (CO_2) than conventional steel on a weight basis (Das, 2011; Han, 2011; Kelly et al., 2015; Murphy, 2008; Suzuki and Takahashi, 2005; Witik et al., 2011b) because of the high energy intensity related to CFRP production. It is also found that the generation of solid and hazardous wastes in the production of lightweight fuel-efficient vehicles would be greater than for conventional materials (Tonn et al., 2003). Life cycle assessment (LCA) is a widely accepted tool in examining vehicle lightweighting viability in the full life cycle perspective (Dubreuil et al., 2010; Geyer, 2008; Kampe, 2001; Keoleian and Sullivan, 2012; Liu et al., 2012; Mayyas et al., 2012; Saur et al., 2000). Several LCA studies have been performed to analyze the environmental impacts for the different vehicle material lightweight designs. However, the environmental performance of lightweight materials are not consistent and have wide ranges reported in the literature. There are also limited understandings of tradeoffs between mass reduction and environmental impacts for different lightweight materials. WorldAutoSteel (WorldAutoSteel, 2011) conducted a comparative LCA study of a Super LIGHT-Car and a simulated AHSS-intensive Golf V with a baseline Volkswagen Golf V. The BIW of Super LIGHT- Car was composed of 53% Aluminum, 36% steel, 7% Magnesium and 4% plastic. The results showed that the AHSS-intensive Golf V concept is the superior design achieving both mass, emission and cost reductions in the full life cycle. Duflou et al. (Duflou et al., 2009) studied the life cycle environmental impacts of lightweight CFRP materials in place of conventional steel structures in BIW production. It showed that CFRP provides environmental benefits over conventional steel but at a longer travelling distance with a breakeven point of 132,000 km.

Despite the benefits as mentioned above, CFRP is difficult to be treated at the end of life due to the nature of crosslinked structure of CFRP and the non-remolding nature of polymer. Currently, recycling has been considered as a prioritized solution to cope with CFRP wastes because the waste materials have the potential value from recovering rather than disposing in landfill or incineration with the possibility to close the loop (Meng et al., 2018a; Meng et al., 2017a; Meng et al., 2017b). It is reported the energy intensity of recycling CFRP can be reduced to the level as that of recycling steel materials (Suzuki and Takahashi, 2005).

Overall, most LCA studies on lightweight vehicle auto part used either secondary life cycle databases, hypothetical data, or literatures data and therefore cannot represent the onsite real design. For a life cycle perspective, the recycling stage is also essential for the comprehensive environmental impact assessment. However, LCI data scarcity still exists in the CFRP production and recycling processes. Moreover, very few LCA studies have been conducted for vehicle lightweighting using the latest onsite investigation data in Chinese sector. To address the above-mentioned issues, we conduct a cradle-to-grave LCA of lightweight BIW design, using primary onsite investigation data in the production stage of materials in 2015-2017, the latest LCI data in the recycling stage in 2017, and China Automotive Life Cycle Database (CALCD) 2015 in this study. Three lightweight BIW Scenarios are compared with conventional steel baseline in terms of primary energy demand (PED) and global warming potential

(GWP).

2 Method

2.1 System Assumption

Statistics from China Automotive Technology & Research Center shows that vehicle BIW contributes for about 30-40% of the total vehicle weight. BIW has a large potential of weight reduction by lightweighting without the influence of the main functionality or comfort level (Das, 2011; Mayyas et al., 2012). In this study, BIW includes body structure, front fenders (both), front doors (both), rear doors (both), hood and decklid. The major BIW components' weight percentage and associated design functions are shown in Table 1. In order to achieve the similar design functions, the weights of the same BIW component vary between Scenarios based on material characteristics. For instance, the weight percentage of the body structure was 74.1% in baseline, and increases to 82.9 % in Scenario III. The weight percentage of Rear doors (both) was 4.4% in Scenario III, nearly 50% reduction comparing with baseline.

Table 1 Major body-in-white components weight percentage and design functions

Component name	Baseline	Scenario I	Scenario II	Scenario III	Main design functions
Body structure	74.1%	72.8%	78.2%	82.9%	Yield strength, bending stiffness, stress and strain, dent resistance, Noise Vibration and Harshness (NVH)
Front fenders (both)	1.4%	1.5%	1.6%	2.2%	Dent resistance, NVH
Front doors (both)	9.3%	10.9%	6.6%	6.9%	Bending stiffness, dent resistance, NVH
Rear doors (both)	8.7%	5.8%	4.3%	4.4%	Bending stiffness, dent resistance, NVH
Hood	2.9%	6.0%	5.6%	2.7%	Bending stiffness, dent resistance, NVH
Decklid	3.6%	3.0%	3.6%	0.9%	Bending stiffness, dent resistance, NVH

This study compares the life cycle PED and GWP of three types of lightweight BIW scenarios with baseline BIW. As shown in Figure 1, the baseline BIW is made of conventional steel with the weight of 430 kg. Based on onsite surveys of Chinese vehicle factories and literature review (EPA, 2012; Malen, 2011; Singh, 2012), three lightweight BIW Scenarios are established. 98.1% of the total BIW weight in

Scenario I is AHSS, 86.1% of the total BIW weight in Scenario II is Al alloy, and 60.0% of the total BIW weight in Scenario III is CFRP. 12.4% of BIW weight in Scenario II and 12.0% of BIW weight in Scenario III are other materials. The other materials other than AHSS, Al alloy or CFRP, are assumed to be steel in this analysis. This study selects Scenario I as AHSS based lightweight design, Scenario II as Al alloy based lightweight design, and Scenario III as CFRP based lightweight design. The weight substitution ratios (Kelly et al., 2015) of three types of lightweight BIW Scenarios relative to the baseline case is 0.8, 0.6, and 0.55, respectively. For all BIW Scenarios and the baseline BIW, a functional unit of one BIW for a compact passenger car with a lifetime of 200,000 km is considered, based on consumer behavior investigations of the China Automotive Technology & Research Centre undertaken in 2013 (CATARC, 2017).

This study is conducted based on ISO 14040/14044 LCA standards (ISO, 2006). SimaPro 8 software is used to develop the life cycle model and conduct the environmental impact assessment. For each scenario, the system boundaries start from the raw material production to manufacturing, vehicle use, and EoL treatment (see Figure 2). The transportation of materials, final part production and treatment of manufacturing wastes are excluded. The manufacture of equipment, including machinery, onsite structures and infrastructure, are also excluded. The latest China Automotive Life Cycle Database (CALCD) 2015 database is used in this analysis. CALCD (Sun et al., 2015; Sun et al., 2017).

2.2 Material Production

Reference materials (steel, AHSS, Al alloy), chemicals (epoxy resin and acrylonitrile) for carbon fiber (CF) production and energy inventory data (electricity) are acquired from CALCD 2015 (Sun et al., 2015; Sun et al., 2017).

Material, energy consumption and the environmental emissions relative to CF production are obtained from onsite surveys of a Chinese CF manufacturer in 2017, which owns the largest annual production capacity of 5,000 tons, accounting for over 50% market share in China. The main production processes of CF include polymerization, ammonification, wet spinning, preliminary oxidizing, carbonization, drying and coiling. Major input materials required for CF production include acrylonitrile (99% by weight) and epoxy resin (1% by weight), with the process yield of 98%. Total electricity and steam consumption per kg of CF during the CF production step are 30.02 kWh and 0.11 m^3 respectively. In addition, the total direct emissions per kg of CF production include 1.21E-04 kg of carbon monoxide and 2.31E-04 kg of hydrogen cyanide. From the survey of a Chinese CFRP factory in 2017, per kg of typical CFRP is made of 56% weight of CF and 44% weight of epoxy resin through the vacuum assisted resin infusion molding (VARI) production process.

2.3 Manufacturing

As shown in Table 2, material and energy consumption of different BIW designs are obtained from onsite surveys of automotive factories in China from 2015 to 2017. In baseline, Scenario I and Scenario II, manufacturing stages of BIWs are similar, including rolling and forging, blanking and stamping and welding. In Scenario III, BIW manufacturing also includes modeling, curing, demolding, adhesive bonding and flanging for CFRP apart from the above stages.

Table 2 Life cycle inventory in the manufacturing stage of four body-in-white designs

Category	Subcategory	Unit	Baseline	Scenario I	Scenario II	Scenario III
Materials	Steel	kg	430.0	0.0	32.0	28.4
	AHSS	kg	0.0	337.5	3.9	18.9
	Al alloy	kg	0.0	6.5	222.1	47.3
	CFRP	kg	0.0	0.0	0.0	141.9
Manufacturing process energy	Electricity	kWh	96.0	105.6	658.9	614.8

2.4 Use Stage

According to vehicle fuel economy test report, the fuel consumption of baseline vehicle is 6.5 L/100 km. The exhaust gas emissions of the baseline vehicle are 0.01 g CH_4/km and 153 g CO_2/km. In this study, the mass-induced fuel consumption of the three BIW scenarios (with powertrain adaptation) are estimated by using the method of Koffler et al. (2010). The EPA combined fuel economy driving cycle (EPA, 2016) is selected to calculate the use phase fuel consumption. The fuel reduction value (FRV) (0.38 L/100kg·100km) of the BIW with the powertrain adaptations is obtained as (Koffler and Rohde-Brandenburger, 2010). The total fuel reduction (C) with powertrain adaptation due to lightweight design can thus be calculated as below.

$$\mathrm{C} = \Delta\mathrm{m} \times \mathrm{FRV} \times D_V$$

where Δm is the mass changes of vehicle (kg), D_V is the vehicle's lifetime distance (200,000 km).

Table 3 presents key parameters of different BIW Scenarios for the estimation of use phase fuel saving and associated GHG emission reduction. The inventory data including extraction and production of gasoline are obtained from CALCD 2015.

Table 3 Key parameters of body-in-white design in the use stage

Parameter name	Baseline	Scenario I	Scenario II	Scenario III
Vehicle curb weight (kg)	1220.0	1134.0	962.0	768.5
Body-in-white weight (kg)	430.0	344.0	258.0	236.5
Total mass reduction	N/A	86.0	172.0	193.5
Lifetime distance (km)	200,000	200,000	200,000	200,000
Life cycle fuel saving (L)	N/A	653.6	1,307.2	1,470.6

2.5 End-of-Life Treatment

From industry survey and experts consultation, 95% of EoL vehicles are assumed to be collected, sorted, shredded and dismantled. The recycling rates of 95 % and 90% are assumed for metals (e.g., steel, AHSS, and Al alloy), and CFRP, respectively. Recycled steel, AHSS and Al alloy are used to avoid primary material production using the recycling model specified in CALCD 2015. Current CFRP waste treatment options vary from conventional landfill, incineration to mechanical recycling and to advanced thermal recycling (e.g., pyrolysis and fluidized bed process) and chemical recycling processes (Oliveux et al., 2015; Pickering, 2006). The advanced thermal recycling technologies currently exist at varying levels of technological maturity: pyrolysis is operated at commercial scale; fluidized bed recycling has been proven at pilot plant scale; and the chemical recycling process is still on a laboratory scale (Meng et al., 2018b). There is greater uncertainty in estimating the life cycle impacts of CFRP recycling technologies due to data scarcity, although data available for fluidized bed systems are comparatively robust from pilot operation at Nottingham and are used in this study.

Fluidized bed CFRP recycling process is a thermal process developed for the recycling of glass fiber and carbon fiber at the University of Nottingham for over 15 years (Pickering, 2006; Pickering et al., 2015). CFRP waste is shredded and fed into the fluidized bed recycling system. In the fluidized bed reactor, the sand bed can decompose the epoxy resin and release the fibers at a high temperature of 450-550°C. Subsequent cyclone separates and collects the fibers from the gas stream out of the fluidized sand bed. The remaining gas stream after separation goes into a high-temperature chamber for full oxidation of polymer content and other organic materials. Energy can be recovered by a co-power generation unit for onsite recycling system use.

In this study, the inventory data for fluidized bed CFRP recycling as previously presented are used (Meng et al., 2017b). It considers likely operating conditions based on a pilot plant developed at University of Nottingham: a plant capacity of 500 t recycled CF/yr; a feed rate of 9 kg recycled CF/hr-m^2; and an air in-leakage rate of 5%. GHG emissions of the decomposition of the polymer content are estimated based on stoichiometric balance assuming all carbon content is oxidized and emitted as CO_2. These parameters correspond to an energy requirement of 7.7 MJ/kg recycled CF (i.e., 1.9 MJ/kg (natural gas) and 5.8 MJ/kg (electricity)) and emissions of 1.68 kg CO_2. Recycled CF can achieve environmental benefits by displacing virgin CF on an assumed 1.1:1 ratio (1.1 kg recycled CF can displace 1 kg virgin CF).

3 Results and Discussion

3.1 Life Cycle Energy Use and Greenhouse Gas Emissions

Figure 4 shows overall changes of life cycle PED and GWP of the three lightweight BIW Scenarios. The Scenario III presents the largest PED and GWP during material production but provides the largest PED and GWP reductions in the use phase, followed by the Scenario II designs. This is primarily because CFRP and Al alloy are energy-intensive materials that consume more energy and emit more GHG than steel during production. In the EoL stage, recycling of these materials could thus counteract some energy use and GHG emissions associated with primary production. Furthermore, due to fuel savings achieved by lightweighting in the use stage, all these three Scenarios can decrease the life cycle energy consumption and GHG emissions compared to baseline in the lifetime distance of 200,000 km. Scenario II achieves the largest reduction in PED and GWP in the full life cycle compared to baseline, followed by the Scenario I and Scenario III.

To further quantify the environmental impact of lightweight designs, life cycle impacts are grouped according to the production (material production and manufacturing stages are combined as production stage), use, and EoL stages (see Figure 5 and 6). The figures present the overall changes of PED and GWP of every lightweight design over travelling distances. The negative slope in Figure 5 indicates the fuel savings and thereby the reduction in total PED due to the lightweight design along the vehicle's lifetime distance. The PED break-even distance for Scenario I relative to the base case is 10,623 km, indicating AHSS design can only achieve PED benefits beyond 10,623 km. In comparison, Scenario II (Al alloy) shows an early break-even distance of 80,713 km while Scenario III (CFRP) has a longer break-even distance of 149,942 km, respectively. This is primarily due to higher energy consumption for BIWs production associated with Scenario II (Al alloy) and Scenario III (CFRP).

Figure 6 depicts the overall change of life cycle GWP related to lightweight designs. Scenario I demonstrates a net GWP benefit from a traveling distance of 9,579 km as it only has slightly higher GWP (80.5 kg CO_2 e) than the base case in the production stage. Scenario II has a far break-even distance of 169,152 km. The GWP break-even distance of Scenario III is 207,568 km exceeding the lifetime of 200,000 km. This indicates Scenario III does not show GWP reduction relative to the base case within the lifetime distance of 200,000 km. Overall, Scenario II demonstrates to be a better option to achieve the largest net life cycle PED and GWP benefits than Scenario I and Scenario III under the present technology case and lifetime distance of 200,000km.

3.2 Sensitivity Analysis

A sensitivity analysis is performance to evaluate the impacts of lifetime distance, mass-induced fuel reduction value (FRV), and substitution ratio on the overall environmental impacts of different lightweight designs (see Figure 7).

The sensitivity analysis of lifetime service distance is conducted by change of ±10% of 200,000 km. The lifetime distance shows to have a significant impact on the overall PED and GWP (see Figure 7). However, it does not alter that Scenario II is the design with lowest life cycle energy demand and GHG emissions amongst lightweight designs in this study. In addition, the PED and GWP benefits of lightweight materials become more pronounced with a longer lifetime distance.

A range value of 0.2 and 0.5 of the mass-induced fuel reduction value (FRV) is considered. FRV has significant impact on the overall PED and GWP of each material and, especially for CFRP. It is found a higher FRV is key to lightweight materials applications, which could offset more of the energy consumption and GHG emissions of the production stage. Despite the range of FRV considered, Scenario II always has the lowest net PED and GWP. However, if the FRV is lower than the lower bound of 0.2, Scenario III would produce higher PED and GWP than the base case. If the FRV is higher than upper bound of 0.5, Scenario III would provide higher PED and GWP reduction than Scenario I.

Former studies (EPA, 2012; Malen, 2011; Singh, 2012) show the substitution ratio ranges of transition from steel to AHSS is 0.21-1.0, from steel to Al alloy is 0.29-0.99, from steel to CFRP is 0.22-0.65. This study uses these ranges of AHSS, Al alloy, and CFRP to analyze the sensitivity of substitution ratios for each scenario, respectively. If the substitution ratio is decreased, which means the weight of lightweight design will lighter than the study before, the life cycle total net PED and GWP for lightweight design will increase. Substitution ratio has greater impacts on the overall PED and GWP for Scenario III than the other Scenarios. A higher substitution ratio in the use stage of Scenario III provides more fuel consumption credits which can afford more impacts of energy consumption and GHG emissions in the production stage.

The CFRP-intensive BIW, Scenario III, is very sensitive to FRV and substitution ratios. This is mainly because the credits of CFRP achieved in the use phase from weight reduction have to mitigate the high-energy-intensive CFRP production, while fuel saving is sensitive to FRV and substitution ratio. Energy intensity of CFRP manufacturing and thus the magnitude of potential environmental saving potentials depends strongly on fabrication parameters such as component design, fiber content, use of recycled material, choice of matrix polymer, and consolidation method (DOE, 2014). Environmentally-beneficial recycling strategies are essential to maximize the credits of lightweight but has less potential to reduce the energy use of recycling process (minimum value of 6 MJ/kg versus 7.7 MJ/kg used in this study) (Meng et al., 2017b). Progress in recycling process optimization and CFRP manufacturing method development are key to achieving the significant environmental benefits that CFRP can contribute to the automotive lightweighting: retaining mechanical properties of recycled CF can increase the substitution ratio in reuse applications, for instance.

4 Conclusions

This study examines the life cycle energy use and greenhouse gas emissions of different lightweight BIW Scenarios compared with the base case using the primary onsite investigation data of Chinese automotive industry in 2015-2017. In the current situation, Scenario II lightweight design (Al alloy based lightweight design) has the lowest PED and GWP during the lifetime of 200,000 km. Scenario I (AHSS based lightweight design) is second favorable lightweight design choice with a break-even distance of around 10,000 km. Scenario III (CFRP based lightweight design) has achieved the lower PED and GWP than baseline, but does not present a break-even point for GWP within the lifetime distance of 200,000 km. In addition, the sensitivity analysis is conducted to evaluate the impacts of some LCA parameters on the total PED and GWP. The results indicate that lifetime service distance, FRV and substitution ratio have large impacts on the total PED and GWP of the three lightweight designs. A combination of longer lifetime distance, larger FRV, and lower substitution ratio are desired for lightweight BIW Scenarios, especially for Scenario III, to achieve the largest PED and GWP reduction compared to the reference case in the full life cycle.

In the near future, the embodied energy of CFRP will be reduced by 50%~83% to ensure and accelerate the use-phase benefits of CFRP (DOE, 2014, 2015). In addition, existing recycling technologies such as fluidized bed process can recover CF with energy requirement as low as 6 MJ/kg (1.5 MJ natural gas and 4.6 MJ electricity) depending on the feed rate of CFRP and the in-leakage of air (Meng et al., 2017b) compared to 7.7 MJ/kg used in this paper, which gives less potential to reduce the energy use of recycling process itself. Therefore, with the future technical developments of CFRP production and recycling technologies, CFRP has the potential to be more sustainable lightweight design with the largest overall net decrease of the PED and GWP values compared to the steel baseline over the vehicle lifetime of 200,000 km.

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Conflicts of interest

None.

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Figure captions

Figure 1 Body-in-white weight of the four designs. Baseline is conventional steel design, Scenario I is AHSS based lightweight design, Scenario II is Al alloy based lightweight design, and Scenario III is CFRP based lightweight design

Figure 2 System boundaries of the body-in-white life cycle

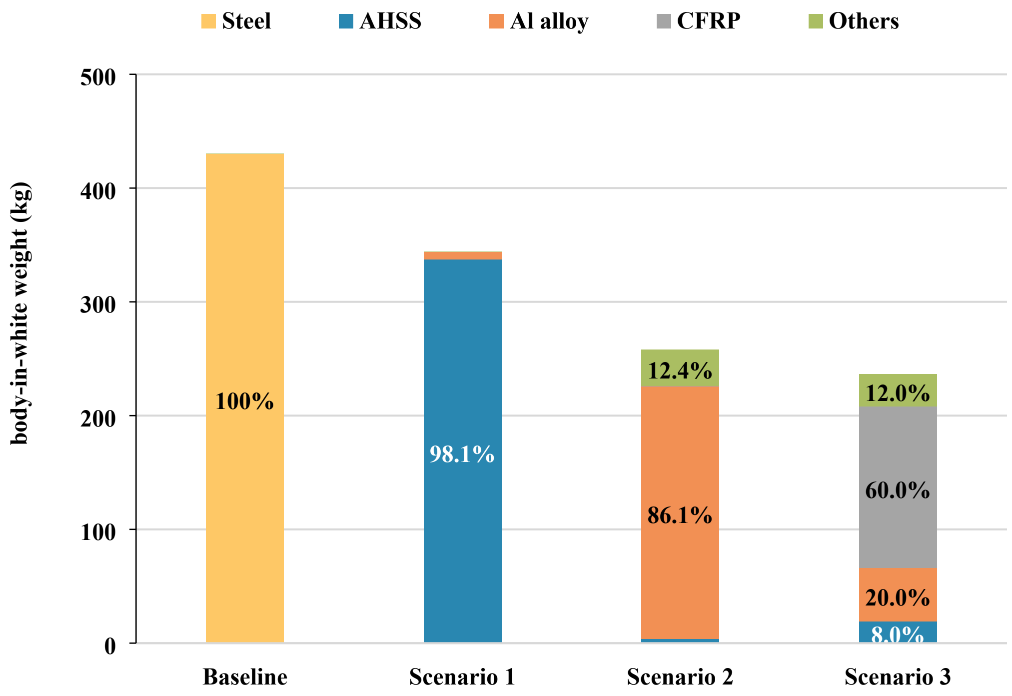
Figure 3 Primary energy demand and global warming potential per kg of material production stage (cradle-to-gate)

Figure 4 Comparison of the life cycle a) primary energy demands and b) global warming potentials of three lightweight BIW Scenarios

Figure 5 Primary energy demand relative to driving distances (up to 200,000km) for three lightweight body-in-white Scenarios, including production and end-of-life stages

Figure 6 Global warming potential relative to driving distances (up to 200,000km) for three lightweight body-in-white Scenarios, including production and end-of-life stages

Figure 7 Sensitivity analysis for some LCA parameters- lifetime driving distance (±10%), FRV (0.2, -0.5) and substitution ratio (0.21-1.0 in Scenario I, 0.29-0.99 in Scenario II, 0.22-0.65 in Scenario III).



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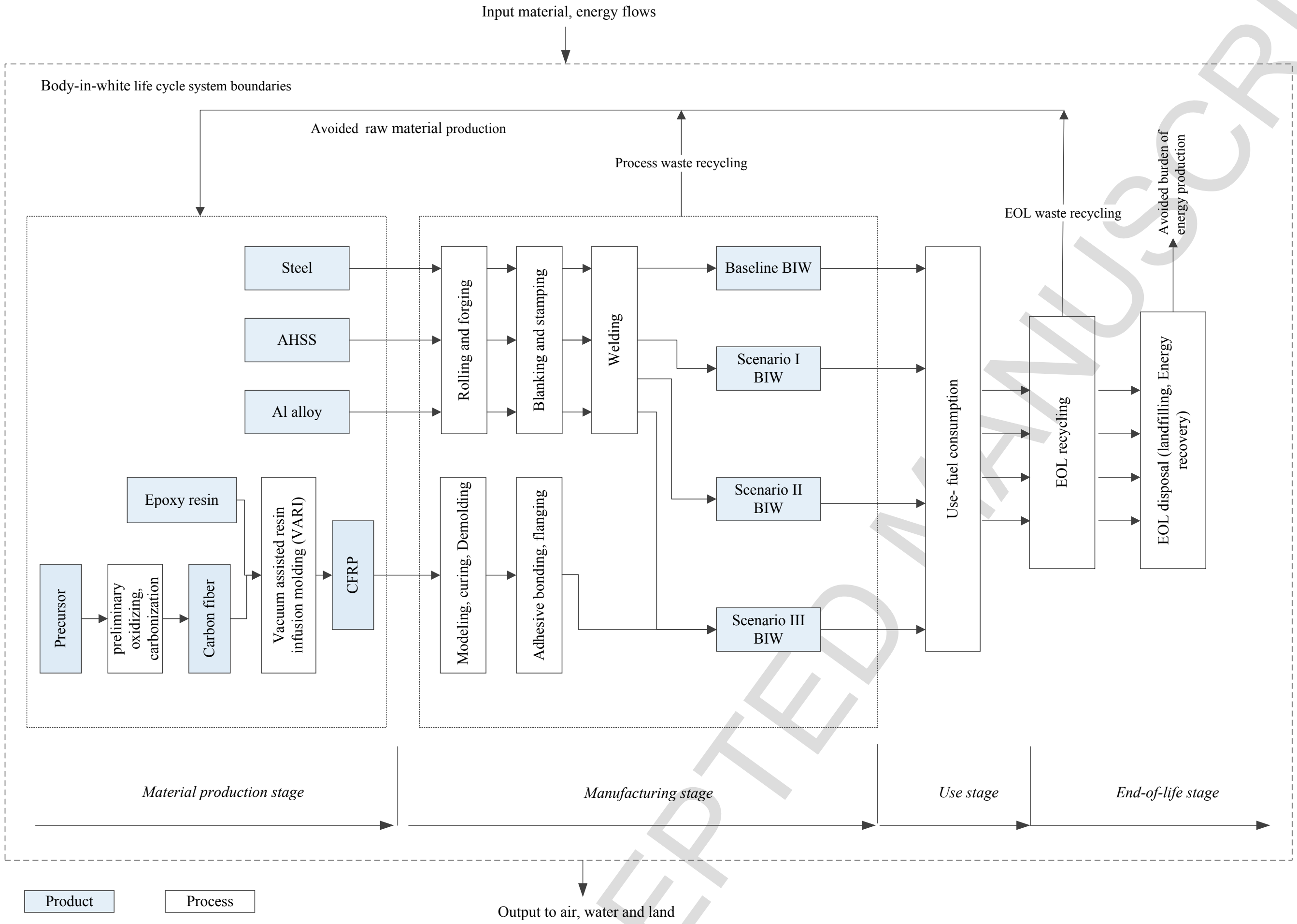

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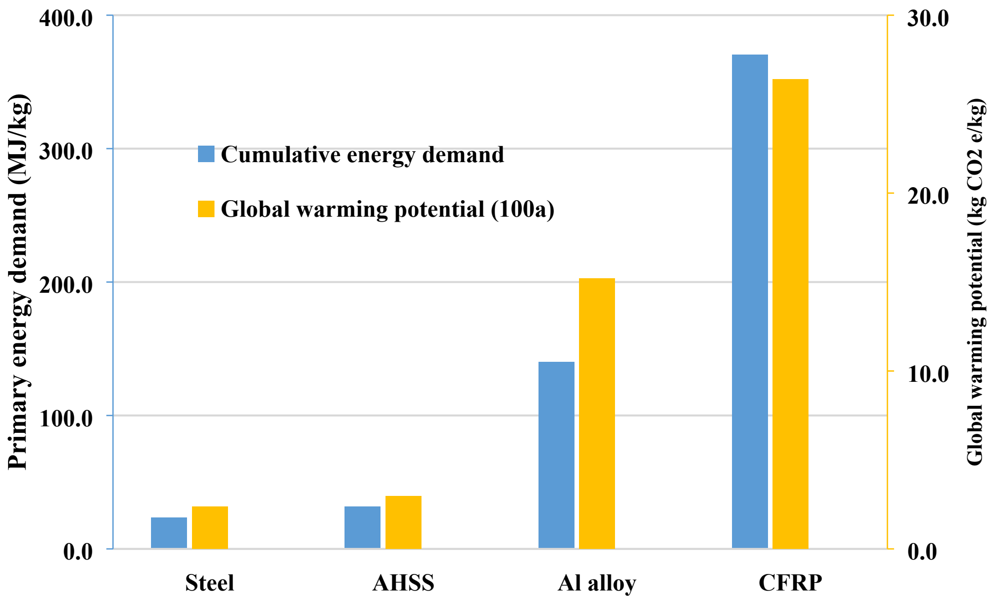

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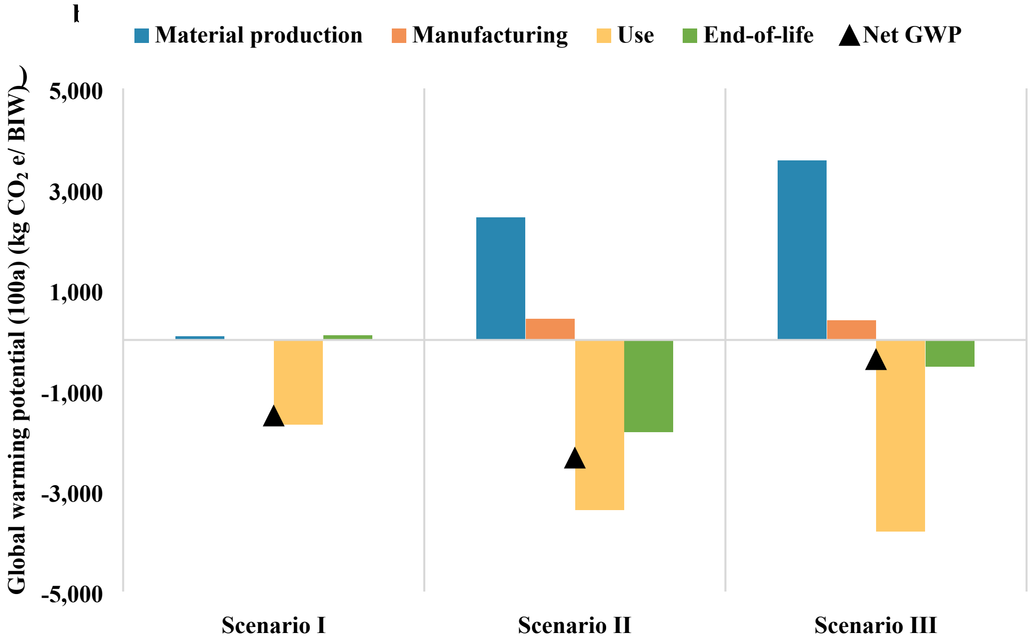

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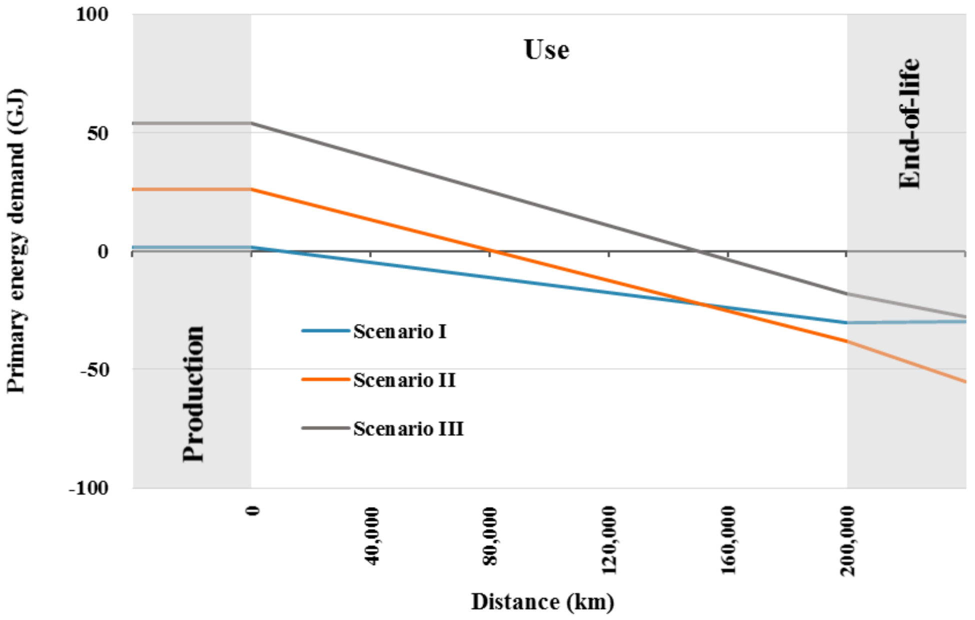


Figure 5 Primary energy demand relative to driving distances (up to 200,000km) for three lightweight body-in-white Scenarios, including production and end-of-life stages

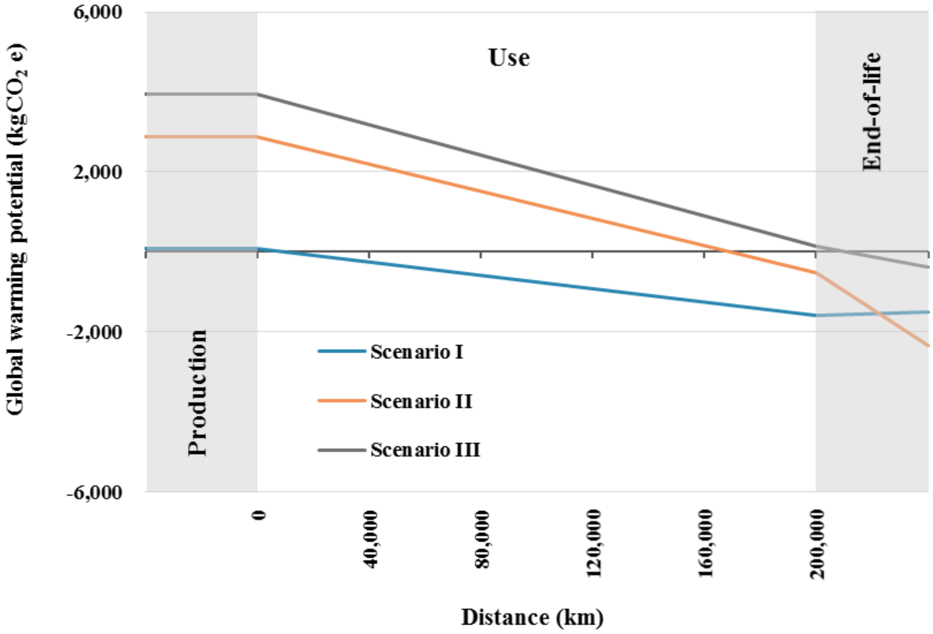
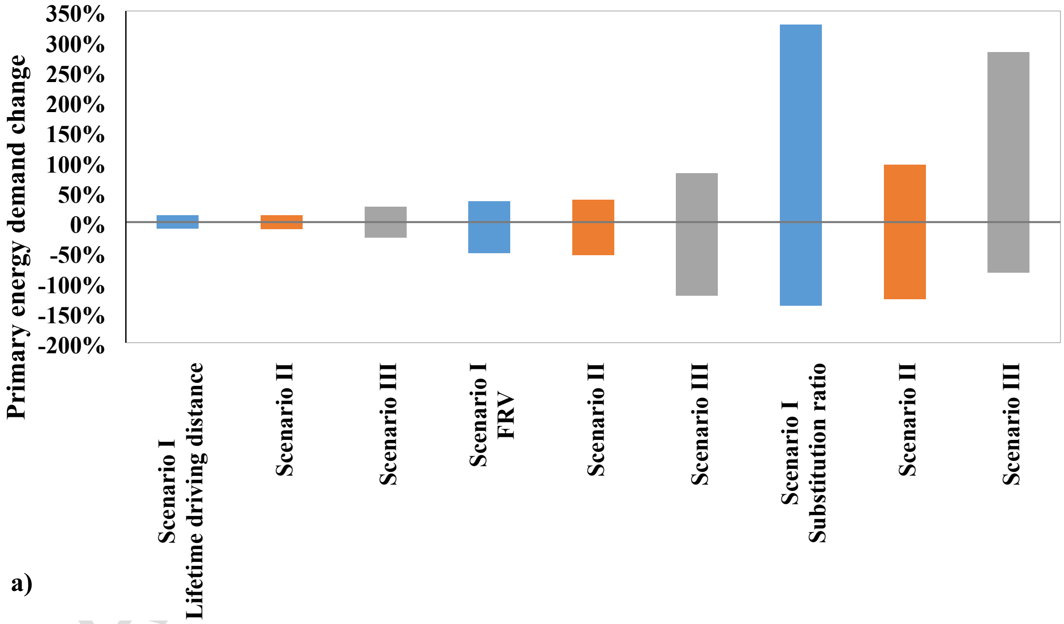
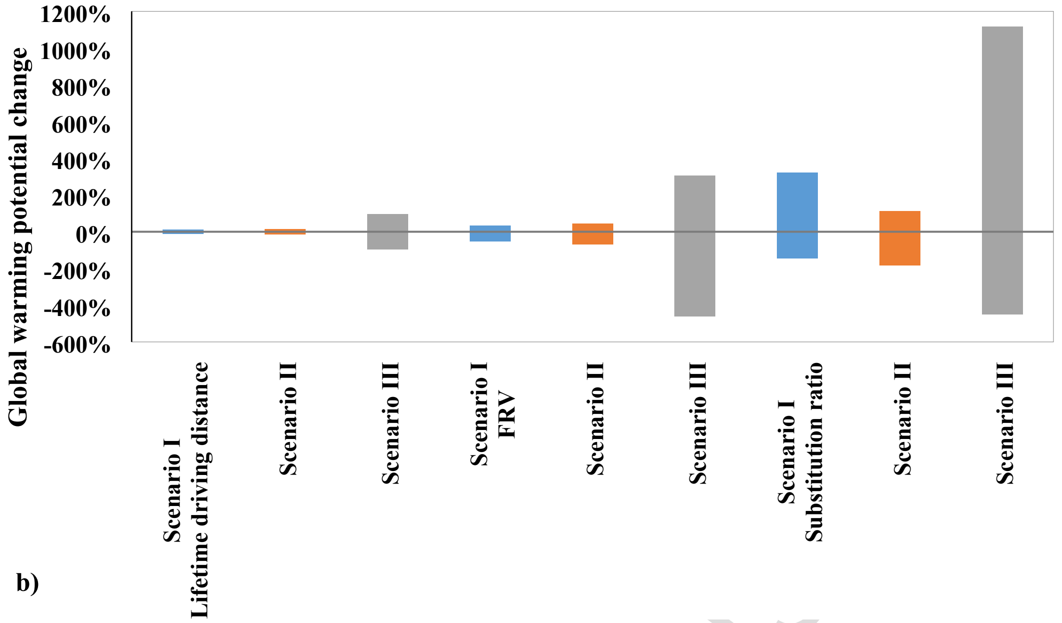


Figure 6 Global warming potential relative to driving distances (up to 200,000km) for three lightweight body-in-white Scenarios, including production and end-of-life stages





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