Life Cycle Assessment of Advanced Materials for Transportation Lightweighting Applications

by

Krutarth Jhaveri

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Thesis committee:

Professor Gregory A. Keoleian, Chair

Research Specialist Geoffrey M. Lewis

Research Specialist John L. Sullivan

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Preface

With transportation being responsible for almost 30% of total U.S. end-use sector greenhouse gas emissions, strategies that can improve the environmental performance of transportation systems are of high value. This research is an exploratory study as part of the Lightweight Innovations for Tomorrow (LIFT) initiative investigating the life cycle environmental performance of advanced lightweight materials for transportation applications. This work focuses on thin-wall ductile cast iron (TWDCI) as a candidate lightweight material and compares its environmental performance to conventional cast iron and cast aluminum in terms of energy and greenhouse gas emissions. A case study approach is used to analyze and compare specific vehicle parts to understand the influential parameters in the part's life cycle impacts. The thesis highlights the tradeoffs that typically accompany lightweighting through lower fuel consumption in the use phase but potentially higher impacts in the production phase. Additionally, it helps emphasize the importance of a life cycle approach in understanding and quantifying the environmental performance of different technologies.

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Nomenclature

b_{EOL}	End-of-life impact per unit mass
B_{EOL}	Total end-of-life impact for part
B_{cred}	Credit due to avoided impact, assuming recycling
b_i	Impact due to component i
B_{LC}	Total life cycle impact
B_{MF}	Total manufacturing impact
B_{MP}	Total material production impact
$b_{P,i}$	Primary material production impact of component i
b_{TFC}	Total fuel cycle impact
B_{use}	Total use phase impact
CCI	Conventional cast iron
Cu	Amount of copper in alloy
D	Distance
EOL	End-of-life
EOLR	End-of-life recycling
η_{cst}	Casting efficiency
η_{mch}	Machining efficiency
η_{sh}	Shredding efficiency at end-of-life
fc	Fuel consumption of part
FC	Fuel consumption of vehicle
fc_o	Fuel consumption of original baseline part
FC_o	Fuel consumption of original baseline vehicle
FRV	Fuel reduction value
FRV^+	Fuel reduction value with resized powertrain
γ	Mass-independent fuel consumption term
GHG	Greenhouse gases
LW	Lightweighting
m	Mass of finished product
m_i	Mass of alloy component i

m_{in}	Total input mass
Mn	Amount of manganese in alloy
% LW	Percentage of lightweighting
RC	Recycled content
Si	Amount of silicon in alloy
TWDCI	Thin-wall ductile cast iron
X_p	Amount of pig iron in alloy

Abstract

Use phase fuel consumption is responsible for the majority of an automobile's life cycle energy consumption and greenhouse gas (GHG) emissions. Lightweighting is an important strategy to reduce use phase fuel consumption and potentially reduce vehicle life cycle impacts. A popular lightweighting technique is material substitution, in which conventional materials (e.g., iron, steel) are replaced with lighter ones (e.g., aluminum, magnesium). Material substitution, however, often results in higher material production impacts. A life cycle approach is useful in evaluating these material tradeoffs and assessing the overall energy and emissions benefits of lightweighting technologies. Thin-wall ductile cast iron (TWDCI) is a lightweighting fabrication technology that can provide comparable weight reduction to aluminum while having better mechanical properties. This study develops a parametric life cycle model to assess the life cycle performance of TWDCI compared to conventional cast iron and cast aluminum in terms of energy (MJ) and GHGs (as carbon dioxide equivalents - kg CO_2e). This model was applied to three lightweighting cases: a differential casing, engine block, and replacement of all iron parts in a light-duty vehicle. Fuel reduction values (FRVs) are used to calculate change in fuel consumption due to lightweighting. A sensitivity analysis on these lightweighting cases is employed to determine the mass reduction required to achieve net life cycle benefits and to show the effect of alloy composition on life cycle energy and emissions. Lightweighting by 2% results in equal life cycle energy and GHGs for TWDCI and conventional cast iron while 37% lightweighting is required for TWDCI to equal cast aluminum impacts. The implications of powertrain resizing afforded by lightweighting are also explored.

1. Introduction and Background

Transportation was responsible for 29% of the nearly 100 quads of US primary energy consumption in 2016 [1]. Fuel consumption during vehicle use is the largest contributor to life cycle energy and greenhouse gas (GHG) impacts of a vehicle [2]–[6]. Regulations and technological improvements have been primary drivers for the reduction of transportation energy and emissions [7]–[10]. Given the dominance of the use phase in the vehicle life cycle, strategies that reduce fuel consumption are of high value in reducing overall vehicle life cycle impacts.

1.1 Mass-dependent Fuel Consumption

Reducing the mass of a vehicle, also known as lightweighting, is a common practice employed to improve the performance of the vehicle through increased fuel economy. Use phase burdens of the vehicle are reduced as less fuel is consumed due to the direct dependence of fuel consumption on mass [11]–[14] and most major auto-manufacturers have committed to reducing the weight of their vehicles [15]. Accurately determining the mass dependence of fuel consumption is challenging and current methods give a wide spectrum of results [16]. This is due to the different assumptions about the drive cycle, vehicle design, powertrain type, and whether the powertrain has been resized after lightweighting for equivalent performance.

The fuel consumption of a vehicle has a direct dependence on its mass [13], [17]–[19]. One way to calculate mass-dependent fuel consumption is through the vehicle's fuel reduction value (FRV) [17]–[19]. FRV quantifies the change in fuel consumption associated with a specific change in mass of the vehicle over a specific distance. Fuel consumption is split into two categories: mass-dependent and mass-independent. The mass-dependent part is a function of the rolling resistance and acceleration loads, and the mass-independent part includes factors such as aerodynamic drag, mechanical losses in the engine, and powertrain losses outside the engine [17]–[19]. Estimates for FRVs of midsized internal combustion engine vehicles lie between 0.15-0.3 L/(100 km 100 kg) [13], [17], [19]–[21]. Reducing the mass of a vehicle reduces the mass-dependent load, resulting in reduced fuel consumption.

1.2 Mass Reduction Techniques

Mass reduction techniques for vehicles have broadly been classified by Mackenzie et al. [15] into two categories: 1) architectural changes and 2) alternative materials. The average weight of light vehicles decreased almost 1,000 pounds between 1975 and 1985 [8]. Cars in the United States saw a major architectural shift during this period, primarily a shift to unibody and front-wheel drive, which played a substantial role in this weight reduction [15]. There was a more than eight-fold increase in the number of front-wheel drive cars between 1975 and 1990 and the number of unibody cars almost doubled in the same period, with front-wheel drive and unibody architecture becoming the norms [15], [22]. High gasoline prices and rising CAFE standards were primary drivers for this weight reduction, as they both incentivized the higher fuel efficiency.

Unibody constructions achieve weight reduction through the elimination of the traditional frame by integrating its structural functions in the vehicle body. Most cars since 1975 have used either a body-on-frame or unibody construction. Body-on-frame construction is mostly found in pick-up trucks while SUV’s and cars mostly have unibody construction. Body-on-frame vehicles are tougher and more stable across uneven terrain while unibody vehicles are lighter and have a simpler construction due to the fewer structural parts required. However, unibody vehicles are more difficult and expensive to repair structurally than body-on-frame vehicles. The amount of weight reduction achieved through unibody constructions varies with vehicle type. Ford ascribed 87 kg of the 112 kg weight reduction to the switch in construction when comparing the Zephyr/Fairmont to the Maverick, with the rest coming from lightweight materials [23]**.** More recently, Mackenzie et al. estimated the weight difference between the two construction types to be around 280 kg after comparing vehicles that were almost identical in most features such as transmission type, drive type, and interior volume but varied in construction type. They also estimated the change in weight resulting from a shift to front-wheel drive to be approximately 296 kg. Smaller weight reductions (≈65 kg) were also achieved through reduction in the engine cylinder count [15]. Since most car companies have already shifted to unibody construction, the focus to achieve lightweighting is currently on other options.

Material substitution is another technique to achieve vehicle mass reduction. Low-carbon steel and iron have been displaced by lighter materials like aluminum, high strength steel, and plastics [15], [24]–[27]. Material replacement is complex in that material properties differ and not all materials can meet required part specifications or are environmentally and/or monetarily too costly. Aluminum has emerged as a popular lightweight material choice in the automotive industry. However, the impacts associated with its production are higher than for heavier metals like iron and steel, a common trade-off for lightweight materials. Relative to iron, it has lower mechanical properties (e.g., strength, stiffness, high temperature performance, damping capacity), and higher cost [28]–[31]. Reducing the thickness of cast iron, or thin-walling, has the potential to make cast iron competitive with cast aluminum in weight while retaining its better mechanical properties [29]. Recent work has shown the possibility of producing thin-wall ductile cast iron less than 3 mm thick [29], [32]–[34] (conventional castings are over 3 mm). Manufacturing difficulties and defects in thin-wall castings have been addressed with various techniques, such as altering alloy composition, varying process temperatures, and selecting appropriate inoculation techniques [29], [32], [33], [35], [36]. One of the key differences between conventional and thin-wall ductile iron castings is alloy composition. Varying the amount of pig iron and alloying elements such as silicon helps control the alloy properties (e.g., tensile strength, nodularity, hardness, castability, and ductility) [31], [33], [34], [36]–[39]. Variations in composition influence production impacts of a given alloy because of the relatively higher material production impacts of materials like pig iron and silicon compared to scrap iron. So it is important to determine if the reductions in fuel consumption from lightweighting (LW) are enough to offset the possible increase in production impacts from alternative alloys.

1.3 Life Cycle Assessment

Life cycle assessment (LCA) is the method of choice in evaluating the performance of products over their lifetime, and it has found extensive use in the automotive industry [40]–[43]. While LCA can be complex, it provides a comprehensive framework for identifying, characterizing, and quantifying the environmental impacts of a product system [2], [4], [13]. Life cycle studies have found a variety of uses with different scopes and extents, and governments and industry have both adopted the tool alike [40], [43]. While there is existing literature on thin-wall ductile iron casting, information on its life cycle performance is lacking. This study presents a parametric model to assess the life cycle performance of thin-wall ductile cast iron compared to conventional cast iron and cast aluminum. Life cycle cases for vehicle lightweighting of selected vehicle components are presented. For each case, the production, use, and end-of-life impacts for the conventional and thin-wall components are calculated using the parametric model. A sensitivity analysis is carried out to determine the break-even point between the increase in production phase impacts and decrease in use-phase impacts by varying the amount of lightweighting. The effect of varying the pig iron content is also presented. Life cycle results are presented using the recycled content allocation approach, and results using the end of life recycling (EOLR) approach are also presented for comparison [44], [45].

1.3.1 Recycling Modeling Approaches

As mentioned above, the two frequently used approaches for modelling the recycling of materials are: 1) the recycled content (RC) or cutoff approach and 2) the end of life recycling (EOLR) or avoided burdens approach. The RC approach takes into consideration the amount of recycled material used in the manufacture of the product. It is based on the premise that recycling is driven by demand for secondary material. The environmental burdens of extraction, beneficiation, and refining of primary material are attributed to the first use of the metal. Subsequent uses of that metal bear the burdens of collection, refining, and transportation of scrap metal. Secondary, or scrap, metals do not incur any of the burdens from primary metal production activities. The RC method, effectively, credits recycling efforts at the production stage through the lower burdens attributed to the share of the material from secondary sources [45].

The EOLR approach considers what happens to the material at the end of its life. The amount of material recycled at the end of the product's life determines how much primary material is not required the second time around. Post-consumer recycling, effectively, offsets the primary production of the material. This is done by crediting the burdens of the avoided primary metal production corresponding to the amount of material recycled. It assumes that there is always a demand for secondary material and that recycling is driven by the supply of secondary material [45]. The material inputs to the product are attributed with the burdens of primary production regardless of any recycled, secondary material being used in the product.

Frischknecht compares the two approaches from different perspectives, showing the RC approach to be risk averse with a strong sustainability concept [44]. The EOLR approach is risk seeking with a weak sustainability concept. The EOLR approach depends on borrowing environmental loans from future generations assuming the material will be reused, resulting in a higher eco-efficiency for primary material, while the RC approach directly links burdens to the product that causes them, resulting in recycled material having a higher eco-efficiency. McMillan et al. challenge the concept of recycling always being driven by the supply of secondary material, arguing that contamination, varying tolerance levels, and dynamic behaviors of materials make it hard to generalize such a concept for all materials [46]. A study on the sustainability of automobiles suggests it is easier and prudent to attribute the burdens based on the specific material used without assuming post-use recycling, and letting the recycled material incur lower burdens when used [47]. It is hard to harmonize the two approaches [44], and this study presents both methods in the model. The results of the case studies are first presented using the recycled content approach, in order to use a risk-averse and strong sustainability method.

2. Method

2.1. System Definition and Metrics

Assessing the life cycle performance of a product involves looking at all life cycle phases, which include material production, manufacturing, use, and end-of-life (EOL). The outputs, or impacts, used to characterize life cycle performance in this study are energy (MJ) and GHG emissions (kg CO_2e). Other impact categories are not considered due to data limitations. The casting process is assumed to be common for thin-wall and conventional cast iron, and so the primary difference is in the alloy material composition and the amount of material needed for casting. Auxiliary materials and processes such as mold preparation and distribution of parts after production are not included because the differences are assumed to be negligible. A sensitivity analysis is used to determine the effects of variation in alloy composition and percentage of lightweighting (% LW).

The parametric model is applied to estimate the life cycle energy and GHG impacts of selected cast iron parts in a mid-sized passenger internal combustion engine vehicle (ICEV) (total mass 1,369 kg) with a baseline fuel economy of 26 miles per gallon (11 km/l) [48]. The vehicle is assumed to travel a lifetime distance of 160,000 miles (257,495 km). The three lightweighting cases considered include the differential casing (5.5 kg), engine block (102 kg), and a case lightweighting all cast iron parts of the vehicle (141 kg) [49]. The life cycle method is applied to evaluate the lightweighting impacts of aluminum for comparison to the cast iron parts, given that aluminum is often a popular lightweight metal as long as it conforms to the required technical standards.

2.2. Life Cycle Phases

The alloy composition of the alloy is important in determining material production impacts. Cast iron is a ferrous alloy containing primarily iron, carbon, and silicon (as ferrosilicon). Other alloying elements, such as manganese, copper, nickel, and magnesium, may be present in smaller quantities. Manganese and copper are included in this study, while the others are neglected due to their negligible amounts (<0.05% by mass each). Iron is present in virgin and scrap form and, due to the composition variability in the literature, the fraction of scrap and virgin material are kept as model parameters. The composition of conventional and thin-wall cast iron used in the model is based on literature [31], [34], [35], [50]–[52] and personal communication with industry experts [53], and is shown in Table **1**.

Table 1: Composition of thin-wall and conventional ductile cast iron (mass percent)

	Pig Iron	**Scrap Iron**	**Si**	**Mn**	**Cu**
Conventional	35	62	2.5	0.3	0.2
Thin-wall	Variable X_p	100 – X_p – Si – Mn - Cu	4.0	0.3	0.2

Material production impacts are taken from Argonne National Lab’s GREET data and the LCA software SimaPro [54], [55]. Figure **1** shows the energy and emission impacts for material production of materials used in iron casting.

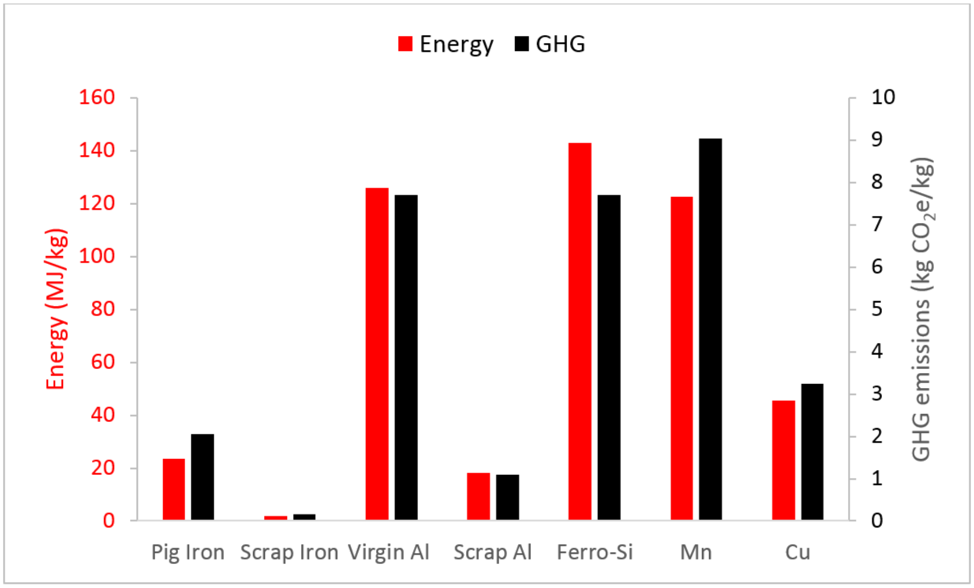

Figure 1: Energy and GHG emissions for different materials per kg mass

A weighted average is used to calculate the alloy's material production impact, B_{MP}, for an input mass of m_{in}, which is given as:

$$B_{MP} = \sum(m_i \times b_i) \tag{1}$$

where m_i is the mass of alloy component i in the total alloy mass and b_i represents its impact (energy, GHG). The input mass can be related to the individual material masses as:

$$m_{in} = \sum m_i \tag{2}$$

Due to production process losses, m_{in} can be related to the mass of finished product, m, as:

$$m_{in} = \frac{m}{\eta_{cst} \times \eta_{mch}} \tag{3}$$

where η represents the efficiency of a process and subscripts *cst* and *mch* indicate the casting and machining processes. The efficiencies used here are η_{cst} = 0.93 and η_{mch} = 1. The manufacturing phase includes melting, casting, and machining the part. The impacts per kg mass of product for these processes are calculated using data from the U.S. LCI dataset and GREET [54], [56]. The manufacturing impacts for a finished part, B_{MF}, are calculated as:

$$B_{MF} = \left(\frac{b_{cst}}{\eta_{mch}} + b_{mch}\right) \times m \tag{4}$$

where b_{cst} and b_{mch} are the casting and machining impacts per unit mass. Use-phase impacts are modeled using FRVs. Fuel consumption (volume of fuel), FC, for conventional cars and light duty trucks of mass M is calculated as [17], [27]:

$$FC = (FRV \times M + \gamma) \times D \tag{5}$$

where the FRV term accounts for the mass-dependent fuel consumption and γ accounts for the fuel consumption independent of mass. This study focuses on the effect of change in mass and hence concentrates on the mass-dependent fuel consumption. For completeness, the mass-independent fuel consumption is calculated in the supplementary information (SI). The vehicle part's share of the mass-dependent component of fuel consumption is a function of part mass, FRV, and total distance traveled (D): $fc = FRV \times m \times D$. The change in mass of the vehicle (ΔM) is equal to the change in the mass of the part (Δm). The change in fuel consumption of the vehicle, ΔFC, and change in fuel consumption, Δfc, due to lightweighting of the part is calculated as:

$$\Delta FC = FRV \times \Delta M \times D = FRV \times \Delta m \times D = \Delta fc \tag{6}$$

and the fuel consumption for the lightweight part, fc, relative to its original value fc_o, is:

$$fc = fc_o - \Delta fc \tag{7}$$

Fuel consumption for the lightweight vehicle is equal to FC_o (its original fuel consumption) minus ΔFC. Lightweighting often leads to powertrain resizing, which can further reduce use-phase impacts, as discussed in the SI. FRV used in this study is 0.21 L/(100 km 100 kg) (without powertrain resizing) [21]. Total fuel cycle energy use and GHG emissions are based on upstream impacts from fuel production (extraction, refining, and delivery) and fuel combustion during use. Total fuel cycle impacts, b_{TFC}, for gasoline are 151.9 MJ/gallon (40.1 MJ/l) and 11.01 kg CO_2e/gallon (2.91 kg CO_2e/l) [48] (calculations are included in the SI). Use-phase impacts are calculated as:

$$B_{Use} = b_{TFC} \times FC \tag{8}$$

At end-of-life, automobiles are 85% recyclable [47], [57]. End-of-life processes include dismantling, shredding, material separation, and post processing. Separation and post processing are not modeled in this study as these impacts are allocated to future use of the recycled material. The efficiency for shredding, η_{sh}, is assumed to be 0.95 [47]. Impacts are estimated as 3.5E-03 MJ/kg and 8.27E-04 kg CO_2e/kg for dismantling, and 0.1 MJ/kg and 0.028 kg CO_2e/kg for shredding [45], [57]. The distance the dismantled hulk is transported from the dismantler to the shredder is assumed to be 100 miles [57]. Impacts associated with transportation via a short-haul diesel truck are estimated as 2.27E-03 MJ/kg-mile and 1.2E-04 kg CO_2e/kg-mile [57], [58] . The EOL impact per unit mass, b_{EOL}, includes all the above processes (dismantling, transportation, shredding). Total EOL impacts for a part of mass m (regardless of material composition) are:

$$B_{EOL} = b_{EOL} \times m \tag{9}$$

The recycled content approach to end-of-life modeling allocates impacts when they are incurred, and the system boundary ends at shredding. Use of recycled material in this system and related impacts for recycled (secondary) material processing are accounted for in the material production phase. The end-of-life recycling (EOLR) approach assumes that the material will be recycled and reused, precluding the need for the production of new material and so a credit is given for the avoided material production impacts. It also assumes that all material used for the production of the part is primary material and attributes the material production with primary impacts per unit mass, b_P. Impacts for material production using the EOLR approach are calculated as:

$$B_{MP}^{EOLR} = \sum(m_i \times b_{P,i}) \tag{10}$$

The amount of material recycled, m_{rec}, is calculated as a product of the shredding efficiency and mass of finished product:

$$m_{rec} = m \times \eta_{sh} \tag{11}$$

The composition of the recycled material is assumed to be the same as the part and so the credit, B_{cred}, is calculated as:

$$B_{cred} = \sum(m_{rec,i} \times b_{P,i}) \tag{12}$$

Since the recycling avoids the production of new material, the credit is placed in the material production phase.

2.3. Total Life Cycle

The total life cycle energy and GHG impacts are calculated as a sum of impacts from each phase as:

$$B_{LC} = B_{MP} + B_{MF} + B_{Use} + B_{EOL} \tag{13}$$

The parametric model using the recycled content approach for a part of mass *M* is:

$$B_{LC} = \frac{\Sigma(m_i \times b_i)}{\eta_{cst}\eta_{mch}} + \left(\frac{b_{cst}}{\eta_{mch}} + b_{mch}\right) \times m + b_{TFC} \times fc + b_{EOL} \times m \tag{14}$$

and the EOLR model is:

$$B_{LC} = \frac{\Sigma\left(m_i \times b_{P,i}\right)}{\eta_{cst}\eta_{mch}} - \sum\left(m_{rec,i} \times b_{P,i}\right) + \left(\frac{b_{cst}}{\eta_{mch}} + b\right) \times m + b_{TFC} \times fc + b_{EOL} \times m \quad (15)$$

Equations **(14)** and **(15)** represent a part's share, by virtue of its mass, of a vehicle's life cycle impact according to the recycled content and EOLR approach respectively.

2.4. Cast Aluminum

Cast aluminum parts are significantly lighter than cast iron parts. The substitution ratio used in this study is that a cast aluminum part weighs 0.55 times an otherwise identical conventional cast iron part [3], [26], [59]. The modeling approach for cast aluminum parts is the same, calculating impacts associated with each phase before summing them to determine total life cycle results. Most aluminum (60-70%) used in vehicles is recycled [60], so the amount of secondary aluminum in a part, a parameter in the model, is assumed to be 65%. Material production impact data for primary and secondary cast aluminum are taken from GREET [54]. Material production energy is 125.8 MJ/kg for primary and 18.1 MJ/kg for secondary aluminum. GHG emissions from material production are 7.7 kg CO_2e/kg for primary and 1.1 kg CO_2e/kg for secondary. The manufacturing (casting and machining) energy and GHG emissions are the same for both primary and secondary aluminum and are 11.1 MJ/kg and 0.7 CO_2e/kg. Casting and machining efficiencies for cast aluminum are assumed to be 0.9 and 1 respectively [54]. Finished cast aluminum products from primary aluminum have energy impacts of 150.4 MJ/kg and GHG emissions of 9.3 kg CO_2e/kg. The impacts for finished cast aluminum product from recycled aluminum are 31.2 MJ/kg energy and 1.9 kg CO_2e/kg GHG emissions. Equations presented above for cast iron are applied to calculate the per-phase and total life cycle impacts for cast aluminum.

3. Results and Discussion

3.1. Total Life Cycle

Lightweighting (LW) and all reported results are specific to the part(s) and not for the entire vehicle, unless specified. All results reported in this section assume 10% LW and 50% pig iron content for TWDCI. The sensitivity analysis in section 3.2 considers variation in % LW and pig iron content. A 10% mass reduction in all cast iron parts of the vehicle is equivalent to a 1.03% mass reduction of the entire vehicle.

Figure **2** shows, for all cast iron parts in the vehicle, the energy by life cycle phase for conventional cast iron (CCI), thin-wall iron, and cast aluminum, and also the total life cycle results.

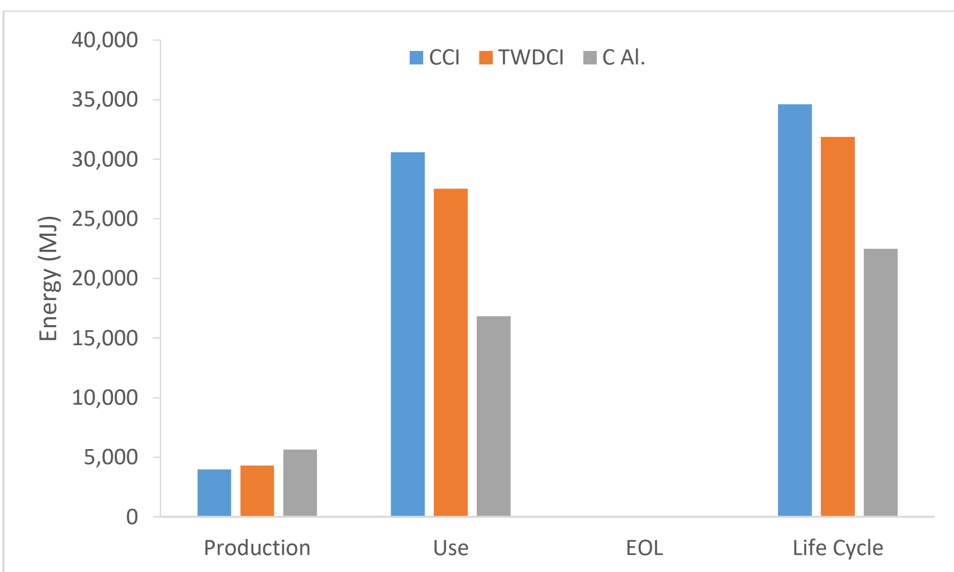

Figure 2: Life cycle energy (MJ) for all cast iron parts of the vehicle – by phase and total (recycled content approach)

The production (material production + manufacturing) energy for conventional cast iron (CCI) is 3,980 MJ (calculation details are included in the SI). When replaced with TWDCI, production energy increases to 4,310 MJ, and increases even further for cast aluminum (5,650 MJ). The higher production energy for TWDCI compared to CCI is due to the higher pig iron and alloying element content and the greater material production energy requirements for these materials.

Use phase energy, primarily determined by the amount of fuel consumed, is 30,600 MJ for CCI, significantly more than CCI production energy. This is reduced to 27,500 MJ when replaced by TWDCI, a 10% reduction compared to CCI that is due to the reduction in fuel consumption from 762 L to 686 L of gasoline. Replacing with cast aluminum reduces the fuel consumption to 419 L and use phase energy to 16,800 MJ, a reduction of 45% compared to CCI. As per equations **(14)** and **(15)**, our model considers only mass-dependent fuel consumption for the use phase and so the use phase energy reductions are proportional to the reduction in mass. The reductions in use phase energy for both TWDCI and cast aluminum are large enough to offset the increase in the production energy for these alloys. Note that the fuel consumption and energy reductions presented above are specific to the mass-dependent fuel consumption applied to those parts. The lifetime fuel consumption (including mass-independent fuel consumption) of the vehicle is 23,300 L. Mass-independent FC is presented in the SI. The reduction in total vehicle fuel consumption is 0.3% when all the cast iron parts of the vehicle are replaced with TWDCI and 1.5% for replacement with cast aluminum.

The EOL energy impacts are too small to show up in the figure. CCI incurs an energy impact of 32 MJ compared to 28 MJ for TWDCI and 17 MJ cast aluminum. The EOL impacts, like use-phase impacts, are only dependent on mass and hence vary proportionally with change in mass. Due to rounding, the percentage energy reductions don't appear to be equal to % LW.

When analyzing the distribution of life cycle energy impacts across phases, it is clear that the use phase dominates, and the reduction in energy achieved in the use phase for the lighter alloys is significant enough to achieve a net benefit in total life cycle energy. TWDCI incurs a total life cycle energy impact of 31,900 MJ compared to 34,600 MJ for CCI, an 8% reduction. Cast aluminum, with total life cycle energy of 22,500 MJ, achieves a 35% energy reduction compared to CCI. When comparing the energy reduction achieved through lightweighting of cast iron parts of the vehicle to the total life cycle energy of the entire vehicle, the savings are lower. This is so for two reasons: 1. all the cast iron parts (141 kg) account for only a small fraction (10%) of the total mass of the vehicle, and 2. Only part of the vehicle fuel consumption is due to vehicle mass. The entire vehicle has a life cycle energy impact of 1,000 GJ [54] and the reduction in vehicle life cycle energy through substitution with (10% LW) TWDCI is 0.26%. When substituting with cast aluminum, the reduction is 1.2%. The sensitivity analysis below (in section 3.2) explores the effect of variation in % LW on life cycle energy. The presented life cycle results translate to a fuel/mass elasticity of 0.32, which in this case means that a 10% weight reduction (without powertrain resizing) reduces fuel consumption by 3.2%. This falls within the range found in the literature [16].

The GHG impacts for all the cast iron parts, shown in Figure **3**, follow the same trend as energy over all life cycle phases. GHGs emitted during the production of CCI are 300 kg CO_2e. Production of TWDCI emits more GHGs with 330 kg CO_2e, and cast aluminum production has GHG emissions of 350 kg CO_2e. The use phase GHG emissions are highest for CCI (2,220 kg CO_2e) followed by TWDCI (2,000 kg CO_2e) and cast aluminum (1,220 kg CO_2e). Use phase emissions are directly proportional to the fuel consumed, and CCI has the highest fuel consumption due to its higher mass. The cast aluminum parts have the lowest fuel consumption. The EOL emissions are significantly lower than other phases: 5 kg CO_2e for CCI; 5 kg CO_2e for TWDCI; 3 kg CO_2e for cast aluminum. Total life cycle emissions are 2,530 kg CO_2e for CCI, 2,330 kg CO_2e for TWDCI (an 8% reduction), and 1,580 kg CO_2e for cast aluminum (a 38% reduction). The relative reduction in emissions when replacing with cast aluminum is not the same as the relative reduction in energy, suggesting that the energy sources used for cast aluminum are lower in GHG emissions. This is confirmed in the fuel and electricity mix for cast aluminum in GREET[54]. Natural gas is the dominant fuel and the electricity used is dominated by renewable sources. The reduction in vehicle life cycle GHG emissions is 0.27% for substitution with TWDCI and 1.3% for substitution with cast aluminum.

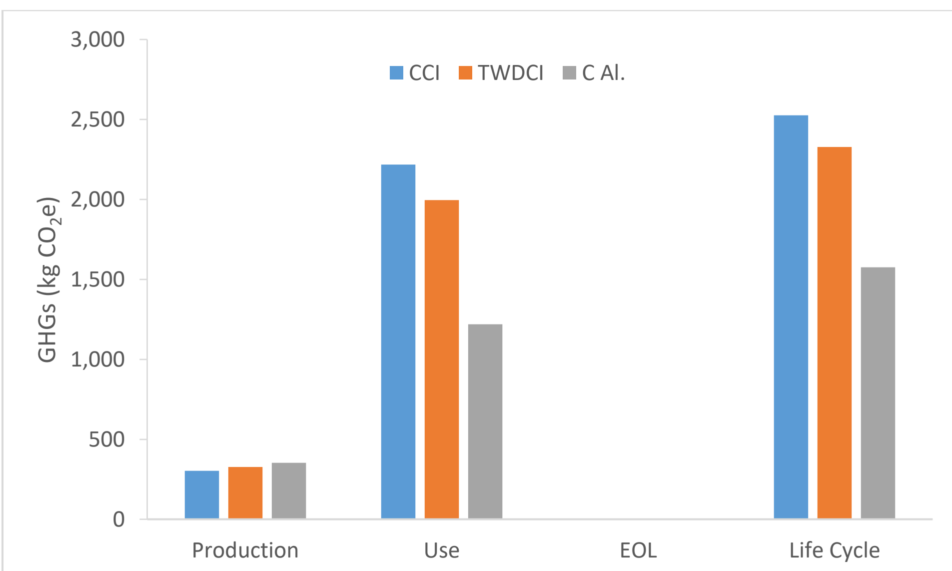

Figure 3: Life cycle GHG emissions (kg CO_2e) for all cast iron parts of the vehicle - by phase and total (recycled content approach)

3.2. Sensitivity Analysis

3.2.1. Mass Variation

The above results were for the case of all the cast iron parts of a vehicle. The two other cases (differential casing and engine block) follow the same trends for energy and GHGs, differing only in their absolute values due to smaller masses of these parts. Figure **4** shows the life cycle energy impacts for all the cases using the different alloys. The relative differences between the different alloys remain the same, so TWDCI results in an 8% energy reduction for all cases, and cast aluminum results in a 35% energy reduction, compared to CCI.

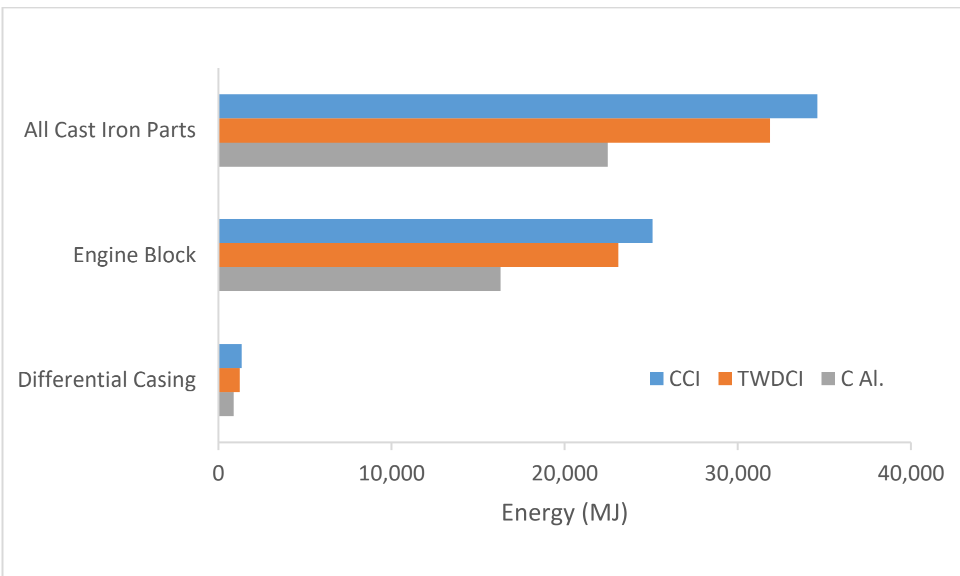

Figure 4: Total life cycle energy (MJ) for different case scenarios (recycled content approach)

The GHGs have a similar trend with CCI consistently being most GHG intensive, followed by TWDCI and cast aluminum. There is an 8% reduction for TWDCI and 38% reduction for cast aluminum. Figure **5** shows the total life cycle GHG emissions for each alloy for the three case scenarios.

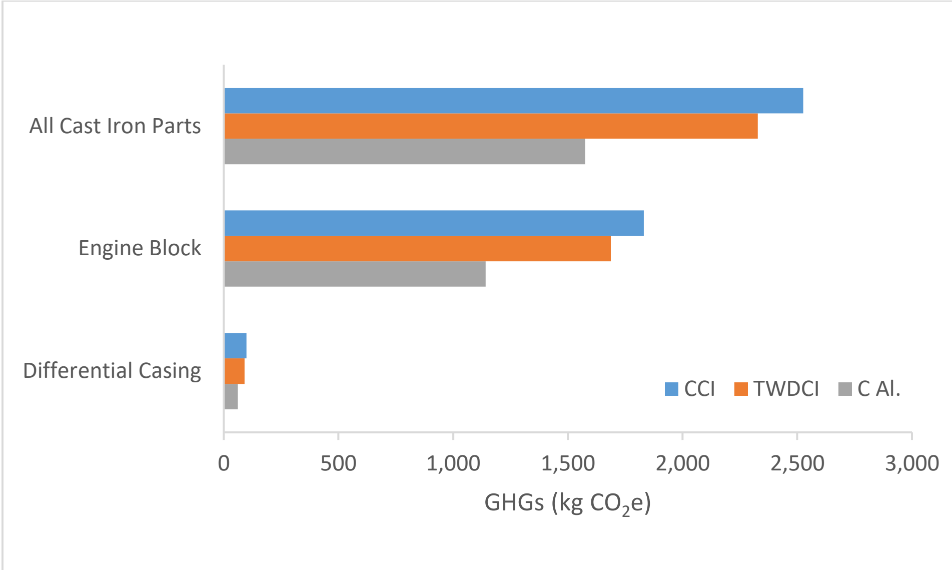

Figure 5: Total life cycle GHG emissions (kg CO_2e) for different case scenarios (recycled content approach)

3.2.2. % Pig Iron and % Lightweighting Variation

This study focuses on comparing TWDCI to other alloys and the results above assumed 10% LW and 50% pig iron content for TWDCI. The sensitivity analysis shows the effect of variation in % LW and % pig iron (% PI) on the life cycle impacts of all the cast iron parts made from TWDCI. Based on literature and industry inputs, lightweighting is varied up to 40%, and % PI in TWDCI is varied between 20% and 80%. The % PI influences the carbon content of the alloy, which in turn affects its strength properties. This could impact the amount of lightweighting possible in parts while maintaining their structural properties. The results compare the effect of variation in % PI and % LW on the life cycle impacts.

Figure **6** compares the total life cycle energy of TWDCI for different % PI to CCI and cast aluminum for all cast iron parts in the vehicle. The influence of % LW on the total life cycle energy is significantly more than that of % PI for TWDCI. While the higher amount of pig iron is one of the primary reasons for the higher production impacts of TWDCI compared to CCI, production impacts make a smaller contribution to total life cycle compared to use-phase impacts, especially for high % LW scenarios, and use-phase impacts can be reduced significantly through lightweighting. 40% LW could result in a life cycle energy reduction of 39% for all cast iron parts, and 1.3% energy reduction in vehicle life cycle energy. A little over 2% LW is required for the 50% pig iron alloy to equal CCI in life cycle energy, and around 37% LW is required for the same alloy to equal cast aluminum. For 80% pig iron, 5% LW is required to equal CCI life cycle energy, and 38% LW is required to equal cast aluminum. The lightweighting amounts required for GHGs to be equal are nearly the same as that for energy.

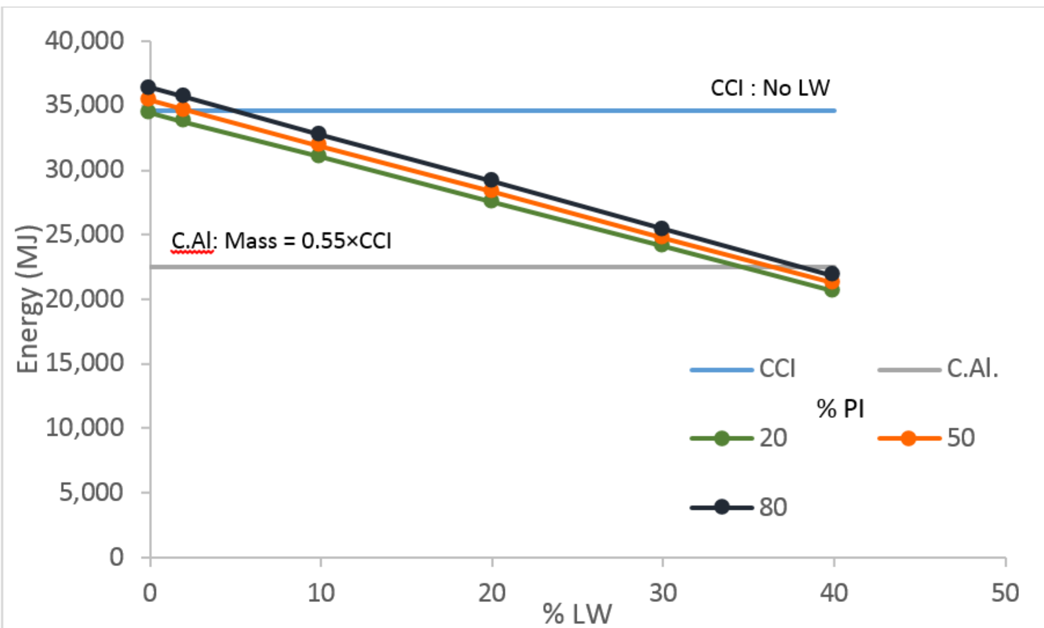

Figure 6: Total life cycle energy (MJ) for variation in % PI and % LW. TWDCI equals CCI at ~2% LW and equals cast aluminum at ~37% LW (recycled content approach)

3.2.3. EOLR Allocation Approach

The previous results were based on the RC approach. The EOLR approach is an allocation technique that assumes that the material at the end of the vehicle or part's life will be recycled, avoiding the extraction of new material, and gives a credit for that recycling. The life cycle EOLR energy impacts are presented in Figure **7** for all cast iron parts of the vehicle where TWDCI has 10% LW and 50% pig iron. The production values include both material production and manufacturing energy impacts associated with the different alloys, and the credit accounts for the impacts avoided due to recycling. Total life cycle energy is 33,000 MJ for CCI, 29,800 MJ for TWDCI (10% lower), and 19,200 MJ for cast aluminum (42% lower). The total life cycle energy is lower for the EOLR approach compared to the RC approach by 5%, for CCI, 7% for TWDCI, and 14% for cast aluminum.

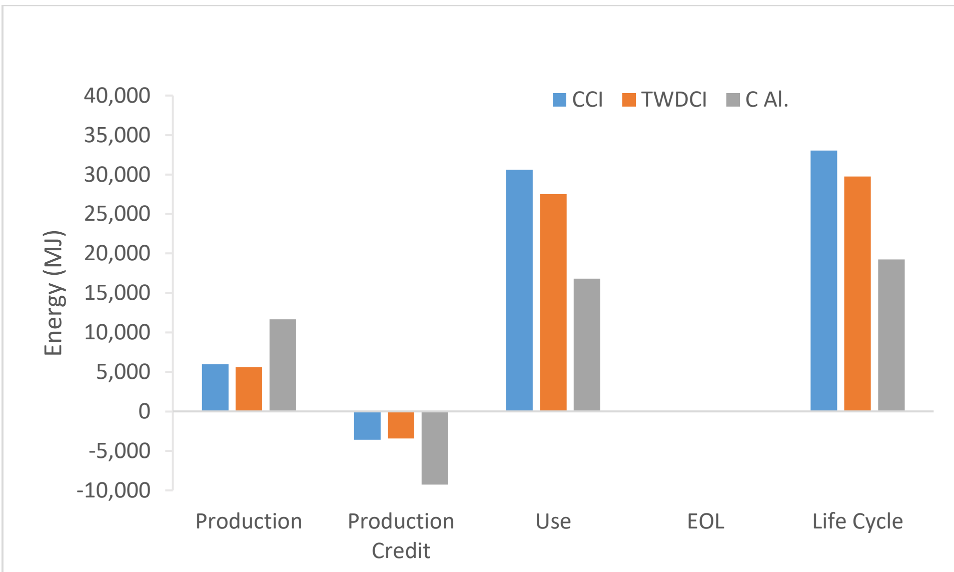

Figure 7: Life cycle energy (MJ) using EOLR approach for all cast iron parts of the vehicle - by phase and total (use phase only by virtue of part mass)

The primary difference between EOLR and RC lies in the production phase where the recycling credit has been accounted for in the EOLR case. As a result, production energy using the EOLR approach is much lower compared to using the RC approach for all alloys. Figure 7 shows the production energy of cast aluminum being comparable to the iron alloys (it was over 30% higher using the RC approach). This is because using the EOLR approach, the only impact incurred is for the material that is not recycled. Due to the cast aluminum parts having a much lower mass, the amount of material lost is also lower compared to the material lost for the iron alloys. However, due to the higher energy impacts per unit mass for cast aluminum, the values are comparable. Another key point is that the production impacts are independent of pig iron content for the iron alloys. Since all the material carries primary impacts, regardless of its grade, the amount of pig iron, and consequently the amount of scrap iron, has no effect as long as the total iron content remains the same. The rest of the life cycle phases have the same energy impacts as the RC approach. The EOLR approach assumes recycling, so the difference between the EOLR and RC approach would decrease if a given product was manufactured from recycled material. The general trend, however, remains the same with CCI having the highest life cycle energy impact and cast aluminum having the lowest.

GHGs follow the same trend as energy, except for the production of cast aluminum. GHGs for cast aluminum material production are the lowest amongst the three alloys. This is because the production of aluminum has lower emissions per MJ of energy required to produce the material compared to pig iron. The fuel and electricity mix used to produce aluminum is responsible for this, as explained in section 3.1. However, the overall production GHGs for all the alloys are significantly lower when EOLR is used instead of the RC approach, as was observed for energy. The use and EOL phases have the same GHGs as the RC approach. Total life cycle GHGs are lowest for cast aluminum (1,370 kg CO_2e), followed by TWDCI (2,170 kg CO_2e), and highest for CCI (2,410 kg CO_2e). The results presented here for the EOLR approach are for all the cast iron parts of the vehicle. The differential casing and engine block cases follow the same trend, varying only in absolute values due to mass differences.

4. Conclusion

This life cycle study found that the production impacts for lighter materials are higher, but the reductions achieved for these mass reduction scenarios in the use phase due to their lower weight more than offset these higher production impacts. This work quantifies the importance of lightweight technology in reducing automobile life cycle impacts. Reduction in total life cycle energy is 8% for TWDCI (50% PI) parts lightweighted 10% compared to the conventional cast iron parts. The vehicle life cycle energy reduction is 0.26% for TWDCI (50% PI) lightweighted 10%. For 40% LW TWDCI (50% PI), sensitivity analysis shows a 39% life cycle energy and GHG reduction for the parts and 1.3% reduction for the entire vehicle. Increasing the amount of % LW, incorporating powertrain resizing, and extending these results to the future fleet of vehicles on road in the United States would effect a significant energy and GHG emissions reduction. The sensitivity analysis shows that only a small amount of lightweighting (2%) is required for TWDCI (50% PI) to equal the life cycle energy of CCI. Around 37% LW is required to equal cast aluminum in life cycle energy. The study also identifies % LW as more influential than % PI in determining life cycle impacts. Cast aluminum consistently shows the best performance in the metrics chosen for this study (energy and GHG emissions). It is important to remember that other factors, including mechanical strength and cost, are primary drivers for material selection since parts must be fit for purpose before their other attributes are of interest. TWDCI has the potential to maintain the desirable mechanical properties of CCI while also reducing life cycle impacts, making it a promising alternative.

Results are based on assumptions regarding process efficiencies, transportation distances, and material composition, which might vary. The parametric model provides the flexibility to accommodate these variations, and to be applied to other materials. It can provide a basis for the evaluation of future materials and lightweighting technologies and assist in policy design incorporating a life cycle perspective. Cost analysis and other environmental impact categories such as water depletion, human toxicity, and eutrophication should be explored in future research.

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Supplementary Information
Production Data

Table 2-SI: Material Production Energy and GHG emissions per kg of finished product

	Energy (MJ/kg)	GHG (kg CO_2e/kg)
Conventional Cast Iron	14	1.1
TWDCI[a] (20% Pig Iron)	13	0.9
TWDCI (50% Pig Iron)	20	1.5
TWDCI (80% Pig Iron)	27	2.1
Cast Aluminum (65% recycled Al)	62	3.8

[a]All TWDCI variants are 10% LW compared to CCI.

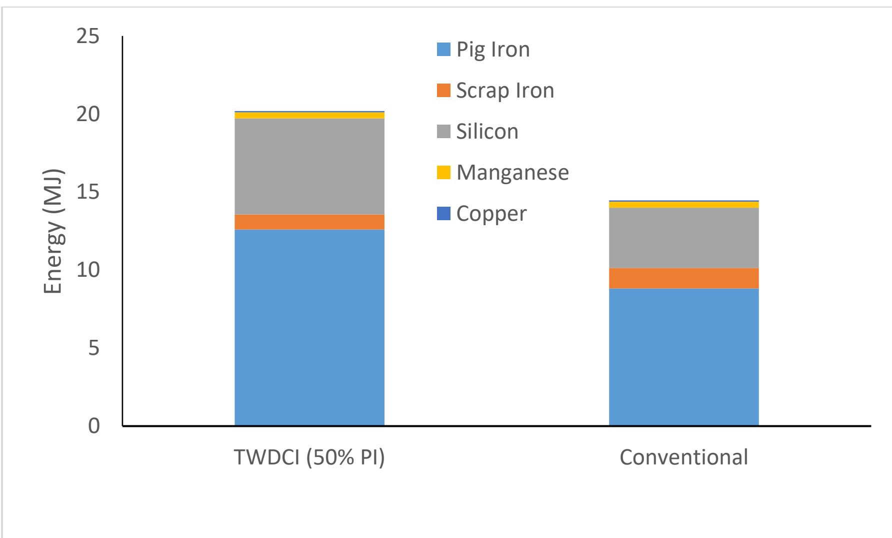

Figure 8: Energy contribution (MJ) of individual materials in material production of 1 kg TWDCI (50% PI) and conventional cast iron

Table 3-SI: Total production (material production + manufacturing) energy and GHG emissions per kg of finished product

	Energy (MJ/kg)	**GHG (kg CO_2e/kg)**
Conventional Cast Iron	28	2.1
TWDCI (20% Pig Iron)	27	2.0
TWDCI (50% Pig Iron)	34	2.6
TWDCI (80% Pig Iron)	41	3.2
Cast Aluminum (65% recycled Al)	73	4.6

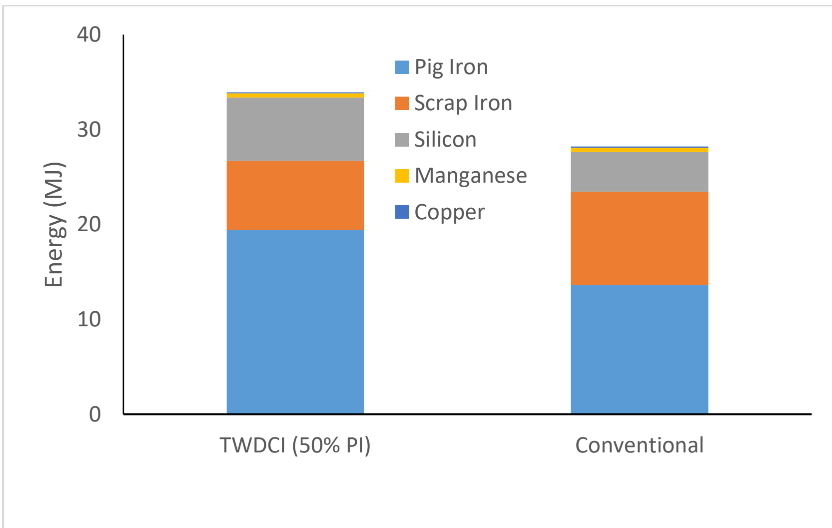

Figure 9-SI: Energy contribution (MJ) of individual materials in total production of 1 kg TWDCI (50% PI) and conventional cast iron

Table 4-SI: Purchased electricity and fuel requirements for casting process (per tonne), including lower heating values (LHV) of fuel and conversion into common units (both mmBTU and MJ)

Electricity/ Fuel Source	**Casting process requirement**[56]		**LHV**[48]	**mmBTU** [48]	**MJ**[1]
Electricity	kWh	1195.0		4.1E+00	4.3E+03
Natural Gas	cuft	7.0	983 (BTU/cuft)	6.9E-03	7.3E+00
Metallurgical Coke	kg	0.2	24,599,422 (BTU/ton)	6.0E-03	6.3E+00
Coal	kg	79.6	22,639,320 (BTU/ton)	2.0E+00	2.1E+03
Diesel	kg	0.8	128,450 (BTU/gal)	3.4E-02	3.6E+01
Gasoline	kg	0.2	112,194 (BTU/gal)	9.1E-03	9.6E+00

[1] Represents purchased energy. Total fuel cycle energy and GHGs for all fuels and electricity taken from GREET[48]

Use Phase Data

Table 5-SI: FRVs drawn from literature

Study	FRV (L/100 km 100 kg)
Ridge 1998[20]	0.14; (0.38 with powertrain adjustment)
Wohlecker et al. 2007[16]	0.15 – 0.7
Koffler & Brandenburger 2010[17]	0.15; (0.35 with powertrain adjustment)
Kim & Wallington 2013[19]	0.2 – 0.48
Koffler 2014[13]	0.16; (0.38 with powertrain adjustment)
Sullivan et al. 2017[21]	0.21

Calculation of total fuel cycle impacts of gasoline

Gasoline well-to-wheel (WTW) impacts (b_{WTW}) (includes all impacts from resource extraction up to and including combustion during use) are (all data sourced from GREET [48]):

Production efficiency = 1,282,334 BTU/mmBTU throughput

GHG = 98,162 g/mmBTU throughput

Gasoline lower heating value (LHV) = 112,194 BTU/gal

Total fuel cycle impacts, b_{TFC}, per gallon:

$$b_{TFC} = b_{WTW} \times LHV$$

Energy, E, is calculated as:

$$E_{TFC} = \frac{1,282,334 \times 112,194}{1,000,000} = 143,870 \frac{BTU}{gal}$$

Converting BTU to MJ, assuming 1 BTU = 0.00105587 MJ:

$$E_{TFC} = 151.9 \frac{MJ}{gal}$$

GHGs are calculated as:

$$GHG_{TFC} = \frac{98,162 \times 112,194}{1,000 \times 1,000,000} = 11.0\ kg\ CO_2e/gal$$

Mass-independent Fuel Consumption

As per equation **(5)** of the main text, total fuel consumption for our base vehicle is given by [17], [27]:

$$FC_o = (FRV \times M + \gamma) \times D$$

The results presented in the main text focus on the mass-dependent fuel consumption. The second component of fuel consumption, which is mass-independent, remains unchanged because the only change in the vehicle is its mass. The mass-independent factor, γ, can be calculated if the other variables in the above equation are known. Using the values mentioned in the main text for FC_o, M, and D, γ is calculated to be 0.06 L/km. The mass-independent fuel consumption is associated with the vehicle as a whole, and not individual vehicle components. The results presented in the main text for different components are mass-dependent in order to understand the effect of mass change. When considering the total fuel consumption of the entire vehicle, the mass-independent component must be accounted for, as has been done in this study for results pertaining to the entire vehicle.

Powertrain resizing

Lightweighting of passenger vehicles is often followed by powertrain resizing to maintain vehicle performance or operational characteristics. From a life cycle perspective, resizing primarily affects the use phase, and the approach to determine changes in use-phase impacts after powertrain resizing remains the same. Literature shows FRV with powertrain resizing to be approximately double the FRV without resizing[13], [18]–[20]. FRV with powertrain resizing, FRV^+, is assumed here to be 0.42 L/(100 km 100 kg), double the value used without resizing. Fuel consumption with powertrain resizing is calculated as:

$$FC = FC_o - (FRV^+ \times \Delta M \times D)$$

It is important to note that powertrain resizing is a lightweighting concept that applies to the entire vehicle and not a single component [17]. As such, the change in fuel consumption due to powertrain resizing is considered in reference to the entire vehicle. For this study, FC_o is 23,300 L, as mentioned in the main text. The change in fuel consumption brought about due to a change in mass is calculated as shown above.

Use-phase impacts are calculated as a product of the fuel consumption and total fuel cycle impacts of the fuel used. Table **6** shows the effect of powertrain resizing on fuel consumption, energy, and GHG emissions for the entire vehicle in which all cast iron parts are substituted for TWDCI and cast aluminum.

Table 6-SI: Change in fuel consumption, use-phase impacts, and reduction in life cycle impacts with powertrain resizing

Alloy	ΔFC (L)	Vehicle Use-Phase Energy (MJ)	Vehicle Use-Phase GHGs (kg CO_2e)	% reduction in vehicle life cycle Energy & GHGs	
				Energy	GHG
CCI	0	931,000	67,600	0	0
TWDCI (50% PI)	152	925,000	67,100	0.6	0.6
Cast Aluminum	686	903,000	65,600	2.5	2.6

The results calculated, when translated to the weight elasticity of the vehicle's fuel consumption, provide a weight elasticity of 0.32 without powertrain resizing and 0.64 with powertrain resizing. This means that reducing the vehicle mass by 10% would result in a fuel consumption reduction of 3.2% without resizing, and 6.4% with resizing. These values are within the range found in other literature [16]. It is important to note that the equation for fuel consumption with powertrain resizing holds for the small changes in vehicle mass examined in this study but the approach taken may not be valid for larger scale reductions in total vehicle mass.

Cast Iron in Automotive Applications

Cast iron - a ferrous alloy consisting of major elements iron, carbon, and silicon - has been used in a large variety of automotive applications since the mid-1900s, mostly in its gray, ductile and austempered ductile iron types [30], [61]. These different types of cast iron vary in their basic strength and hardness brought about by differences in the shape and volume fraction of the graphite phase, and quantities of other alloying elements such as nickel, chromium and molybdenum [62] that are present in a range of 0-1%. **Table 7** below shows the typical carbon and silicon content in these alloys.

Table 7-SI: Carbon and silicon content in different cast iron types [62]

Type	**Carbon**	**Silicon**
Gray	2.5-4.2	1.0-3.0
Ductile	3.0-4.0	1.8-3.0
Compacted Graphite	2.5-4.0	1.5-3.0
Malleable	2.2-2.8	1.2-1.9
White	1.8-3.6	0.5-2.0

Iron was the second most abundant material behind steel in a generic vehicle studied in 1997 [61], [63]. The amount of iron in vehicles began to decrease near the end of the 20th century [61], and was surpassed as the second most abundant material by aluminum in the early 2000s [64]. The primary driver for vehicle lightweighting, as mentioned before, is the concern around global warming and the resultant interest in replacing steel and cast iron with the lighter aluminum. The interest in using iron was, and still is, due to its desirable mechanical properties of strength, ductility, and toughness [30], [62]. It has significant advantages over aluminum in mechanical properties, wear properties, damping capacity, and cost [28], [29]. Ductile iron is able to withstand long term cyclic stress, shown in **Figure 10**, and displays better high temperature resistance than aluminum (**Figure 11**), which is important for automotive applications [28], [29], [31]. Fras et al. highlight the potential to produce cast iron weighing the same as cast aluminum and having the same or better mechanical properties [29]. These cast iron properties can be further improved through austempering heat treatment. Austempered ductile iron is reported to be more than three times stronger than the strongest grade of forged or cast aluminum while its stiffness is around twice that of aluminum. Its density is around 2.5 times that of aluminum and its strength to density ratio suggests the possibility of having a cast iron part lighter and stronger than aluminum [30], [31].

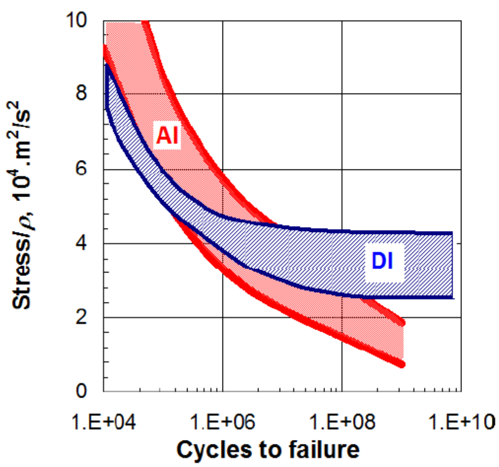

Figure 10-SI*: Specific Stress-Cycles to failure relation for aluminum and ductile iron* [31]

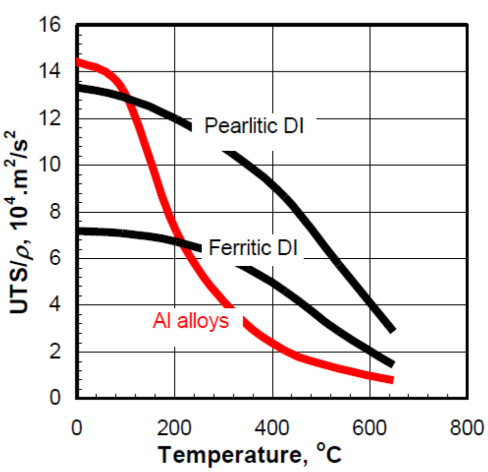

Figure 11-SI*: Ultimate Tensile Strength (UTS) of aluminum and ductile iron* [31]