Substitution of Cast Iron engine components with Aluminium Alloys: A Life Cycle Perspective

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Abstract

Environmental sustainability is nowadays one of the most important global challenges. It is common that the amount of CO_2 emissions is being used as a measure of the environmental impact of vehicles. As a result, manufacturers focus on producing lightweight car components in order to minimize the weight of the vehicles and maximize the fuel economy. As a consequence, car manufacturer designers have started to favour low density materials. However, it is usually the case that the energy footprint of the materials as well as the processes involved in the manufacturing of automotive components is often not assessed. This study focuses on the validity of the claim that lightweight materials are associated with enhanced environmental sustainability by making a full assessment of the energy consumption and CO_2 emissions during the manufacturing and usage stages of diesel and petrol engine blocks made of cast iron and aluminium. For this purpose, inputs from over 100 world experts from across the automotive supply chain have been taken into consideration. Our results show that the usage of lightweight materials is often associated with higher energy consumption and CO_2 emissions. More specifically, the 1.6L aluminium alloy engine block examined only seems to compensate for the additional energy consumed during their manufacturing process after 200,000 km of on-the-road driving compared to the one made of cast iron. Similar trends are observed for the CO_2 emissions.

Introduction

According to recent reports [1], road transport is responsible for about 20% of the total CO_2 emissions in the EU and has increased by more than 20% since 1990. This has led to legislation encouraging the production of lightweight cars in order to reduce the on-the-road emissions. As a result, there is a general perception that lower density materials will contribute towards the reduction of the CO_2 footprint of automobiles. Moreover, when it comes to recycled materials, e.g. aluminium (Al), it is more than common that the energy input required from ancillary processes used in the recycling stages is often being neglected or underestimated [2].

Recently, researchers have focused on the big picture and introduced the term "embodied energy", which is indicative of the energy required for the production of materials using ores and feedstock. Each product has a number of life phases, namely; material production, manufacturing, transportation and use. According to Ashby et al. [3] the "use" phase of an

automobile is the most dominant in terms of energy consumption. However, in the second part of this investigation a comparison is being made between the energy used for the production of 14 kg steel bumper and a 10 kg aluminium one. Their results show that the energy required for manufacturing the bumper made of aluminium is 5 times higher than the corresponding value for the one made of steel. Moreover, the extra amount energy required for the aluminium bumper can be offset after 250,000 km of on-the-road driving. The high embodied energy of aluminium compared to steel is attributed to the energy intensive electrolysis and bauxite conversion stages.

In a similar study, Sorger et al. [4] demonstrated the potential of using cast iron (CI) for manufacturing cylinder blocks. They suggested that CI can significantly contribute towards ecological sustainability and energy balance. The authors clearly highlighted the importance of evaluating the entire product lifecycle ("cradle-to-grave") instead of solely focusing on the "use" phase. As shown in Figure 1 the energy requirements and CO_2 emission for a crankcase made of cast iron are much lower than the corresponding values for the Al casting processes. Finally, the energy savings during the use phase of the lighter Al crankcase were found unable to offset the additional energy demand of the manufacturing phase during the lifecycle of the product.
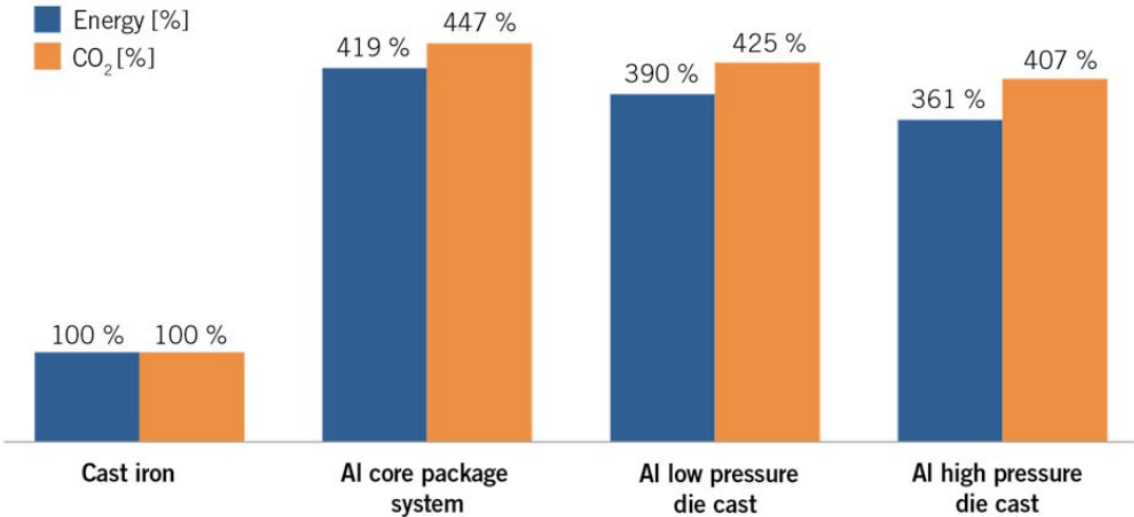

Figure 1: Manufacturing phase – energy requirements and CO_2 emissions for the production of a cylinder crankcase (including consideration of the global recycling rate according to Gesamtverband der Aluminiumindustrie e.V. (GDA) [5]

In this investigation we perform a full assessment of the energy requirements and CO_2 emissions of the "manufacturing" and "use" phases of a 1.6 in in-line 4-cylinder engine block. For this purpose, have compared the cases of (a) a cast iron engine block and (b) an aluminium

engine block. Our results show that there substituting cast iron with aluminium would not contribute to neither energy efficiency nor environmental sustainability as far as the product lifecycle is considered.

Methodology

In order to obtain the required data for this study we performed a wide literature review and contacted more than 100 experts in the automotive industry (engine design consultancy firms, foundries, mining/machining/heat treatment/recycling/impregnation companies, and primary alloy producers). As expected, it was not been feasible all times to collect the required energy data from the aforementioned companies; thus when those data were not available we obtained the required from the multiple sources in the literature.

The selection of the engine type under examination was based on the investigation of Trechow [6] who forecasted that by 2016 4 cylinder engines would increase from about 58% of the world-wide market to about 71%. Moreover, both OEMs and automotive suppliers we contacted suggested that both petrol and diesel 1.6 L in-line 4 cylinder blocks can be characterised as the representative engines of modern vehicles.

In order to select appropriate weight for the four aforementioned engine types we took into account the fact although CI is about 3 times denser than Al, it also characterised by superior mechanical properties (i.e. strength/density and Young's modulus/density ratios). Consequently, CI allows for more compact designs with thinner cross sections. Based on an industry survey we conducted, we selected a 9 kg weight differential and 11 kg differential between the petrol and diesel engine blocks respectively. Taking into consideration the above and the fact that CI is about 3 times denser than Al, it can be concluded that the volume occupied by the CI block is about 55% less than the corresponding volume of the Al block. This results in a reduction of the weight of the ancillary components.

Initial reports based on accepted industry standards have shown that a 5-10% weight reduction can yield 6% fuel savings [7]. However, more recent reports ([8], [9]) indicate that, instead of 6%, a 4.6 % might be achievable while occasionally fuel savings can be as low as 3%. According to a NRC report [10], for 1% and 5% reduction, fuel savings of 0.3% and 3.3% can be achieved respectively. In this study, the value of 4.6% has been adopted.

Embodied Energies

There are discrepancies in the literature regarding the energy required for the formation of primary materials. Allwood and Cullen [2] have suggested values of 170 GJ/tonne and 35 GJ/tonne for primary aluminium and iron respectively. On the other hand, online sources and investigations suggest values ranging between 50 and 100 GJ/tonne for primary aluminium and 35 GJ/tonne for primary iron. In order to select an appropriate value we draw the full

lifecycle of each material and calculated the energy/mass in each step of the process as illustrated in Figure 2. The similar process was followed for iron. According to our calculations 98 GJ and 17 GJ are required for the production of 1 tonne of aluminium and iron respectively.
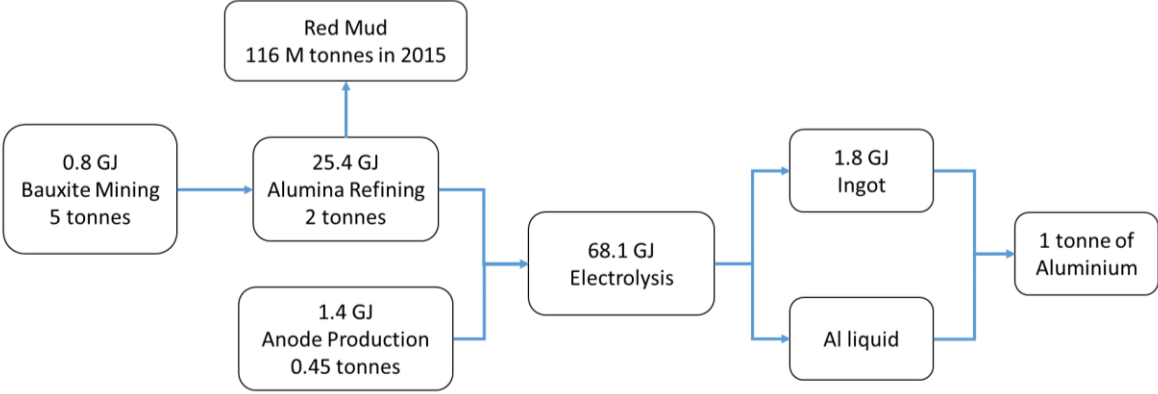

Figure 2: Process flow steps for primary aluminium production and corresponding energy content required to produce 1 tonne of aluminium

Besides raw material, most of the foundries we interviewed used recycled material to make-up the metal charge. The CI foundries interviewed used a high proportion of steel scrap as charge material. Steel scrap was also mixed with scrap from End of Life (EOL) components and fettled methoding systems. In this investigation we considered that in CI foundries the metal charge consisted of 91% recycled material which, depending on its provenance, had an energy content of 10 GJ/t or 4 GJ/t respectively. The Al alloy foundries interviewed used various percentages of recycled material. Low Pressure Die Casting (LPDC) foundries were found to use 100% primary material and at the same time performed no in-house recycling. On the other hand, Low Pressure Sand (LPS) foundries used both secondary ingot and in-house recycled A319 alloy (~35%). Moreover, recycled foundry ingot was used to offset losses; thus we can claim that 100% of the charge material was recycled. In High Pressure Die Casting (HPDC) foundries a high proportion (~27%) of internal scrap was added to A380/383 secondary foundry ingot. Based on the aforementioned recycling rates and assuming the best case scenario for Al foundries, we considered values of embodied energy equal to 32, 24 and 25 GJ/tonne for the LPS, LPDC and HPDC processes respectively.

In addition to primary and recycled materials additional materials have to be used in each one of the casting processes considered in this study (CI, LPS, LPDC and HPDC). In Al alloy foundries CI liners are being used which are either cast in or pressed. According to the feedback received from OEMs participating in our survey pre-machined liners were used. We considered that for the cast liners 95% recycled scrap iron was used which result in an embodied process energy equal to 188 MJ or 12 GJ/tonne for the set of four liners. Moreover,

additional alloying elements were used in ach process type. In Al alloy foundries copper (13.5 GJ/tonne) and silicon (122 GJ/tonne) [11] were used while in CI foundries ferrosilicon (1.6 GJ/tonne) was added to enhance the grain structure and thus the quality of the finished component. Standard sand casting and Low Pressure Sand casting are burdened with additional energy associated with the mining, preparation, recycling, movement and bonding of the sand (2.3 - 5.8 GJ/tonne). We have also accounted for the additional energy required for the recycled sand used for making cores of moulds (0.2 - 1.8 GJ/tonne). The embodied material energy from all sources is illustrated in Figure 3.
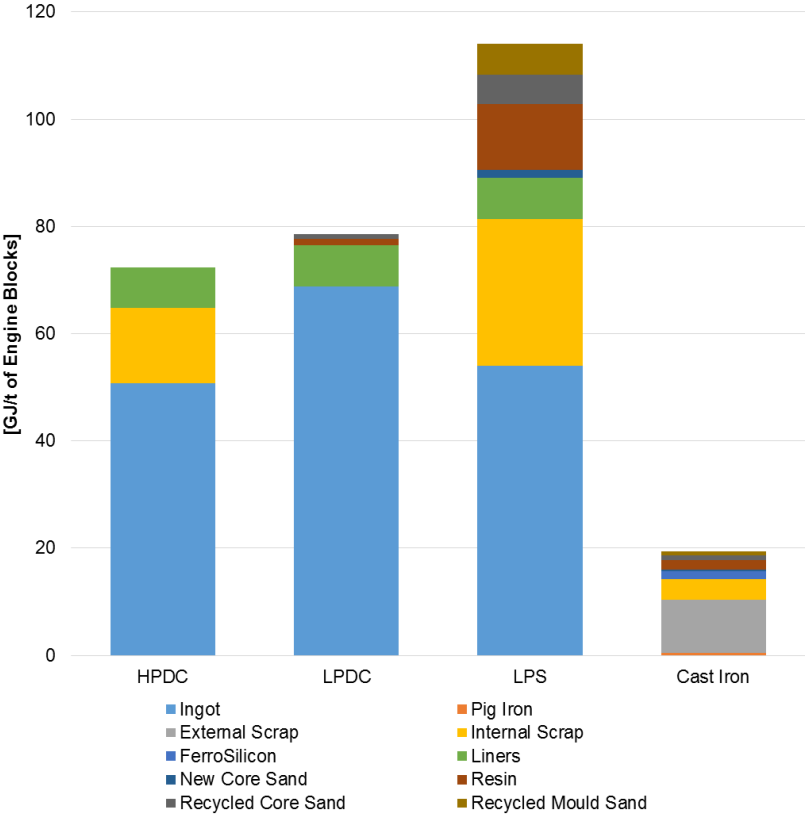

Figure 3: Embodied material energy of each source for each casting process

Process Energies

In order to achieve 100 °C superheat for 1 tonne of Al alloy or CI theoretically 1 GJ of energy is required. However, due to the relatively low efficiency of the furnaces used in foundries (50 - 75%) one would expect that the energy content of the melting process would be of the order of 2 -3 GJ/tonne for both CI and Al. Figure 4a illustrates the melting energy as measured by the interviewed the CI and Al alloy foundries. Besides melting, additional energy is required for holding the liquid metal to allow for different production rates and cleaning to be carried out [12]. The holding energy for Al foundries is much higher compared to CI foundries because of the additional treatments such as degassing and cleaning that have to be carried out (Figure

4b). Moreover, according to the feedback we received from the interviewed foundries we assumed an unrecoverable metal loss equal to 2% for both foundry types.

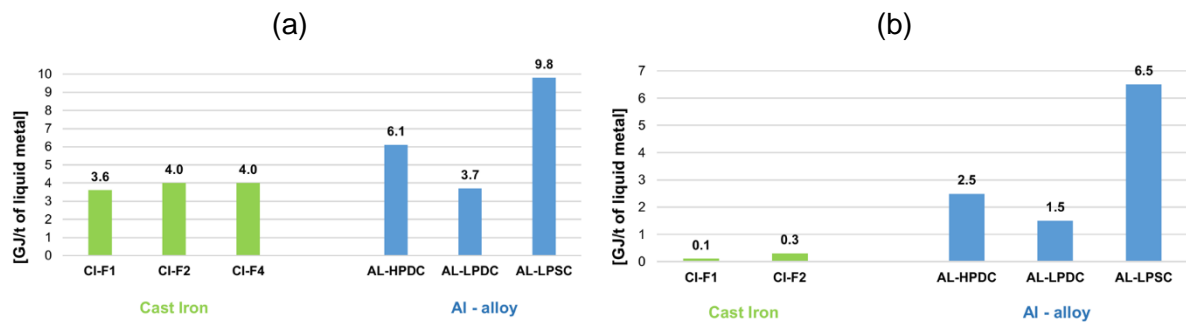(a)   (b)

Figure 4: (a) Melting and (b) holding energies in the interviewed foundries. All of the CI foundries used cupola melting and little variation is exhibited between the measured energy values. The large variation observed in the Al alloy foundries is attributed to the various melting processes adopted.

In all of the aforementioned foundry types with the exception of HPDC foundries, sand cores are being used for the formation of the internal cavities of the engine block. These cores were made of silica sand using the cold box method. In HPDC, cores cannot be used due to the high pressure injection of liquid metal which results in their destruction. For each process, cores with different weights are being used and the energy for their formation energy was found to be in the range between 0.5 and 1.5 GJ/tonne.

One of the most energy demanding post casting processes is heat treatment. In contrast to CI alloys which do not require heat treatment, Al alloys need to undergo heat treatment in order to improve their strength and ductility. Some typical heat treatment processes, such as T6/T7, consist of two stages: (a) heating the component just below the melting point (~550 °C) for up to 5 hours, depending on the maximum cross section thickness and (b) immersing the component in a water, oil or water/polymer bath and "ageing" at a temperature usually close to 200 °C [13]. HPDC components are not usually heat treated although they often undergo a stress relieving treatment with much lower energy content compared to the full heat treatment process. Theoretical calculations as well as feedback from heat treatment companies suggest that for T6/T7 treatments, 3.2-6.1 GJ/tonne of finished casting are required, depending on the furnace energy efficiency. The LPS foundry interviewed used a variant of the full heat treatment process which did not require the cast part to cool down to the ambient temperature but heat treatment was applied directly after casting. As a result the energy content of this process was much lower compared to the conventional heat treatment process (1-2 GJ/tonne).

In addition to heat treatment, the final cast component needs to be machined in order to remove the excess material and attain the desired dimensional accuracy and surface finish.

The machining energy varies significantly depending on the machining parameters used and can be reduced by adding feeders in the areas which are to be machined. We used a simulation tool provided by MAG IAS GmbH [14] to estimate the energy consumption for machining the cast component using various processes and materials. According to the yielded results, the energy required for machining the Al alloy and CI alloy engine blocks would be 2.1 GJ/tonne and 1.6 GJ/tonne respectively.

Miscellaneous energies

Miscellaneous energy consists of the energies associated with the facility operation and other ancillary processes such as heating, lighting etc. Figure 5 represents the data collected from the foundries interviewed.
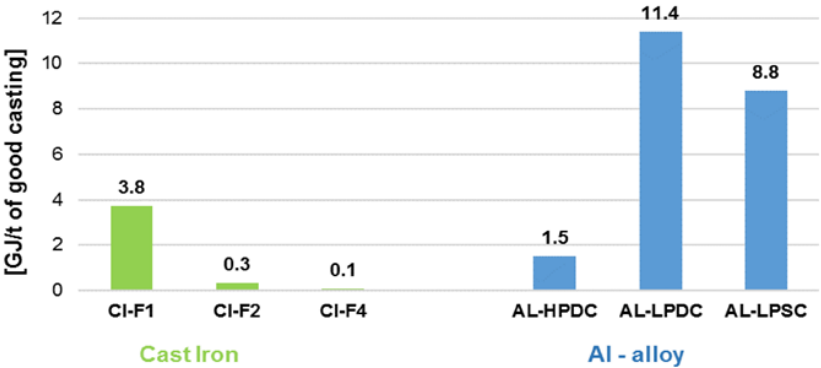

Figure 5: Miscellaneous energy monitoring at the foundries interviewed
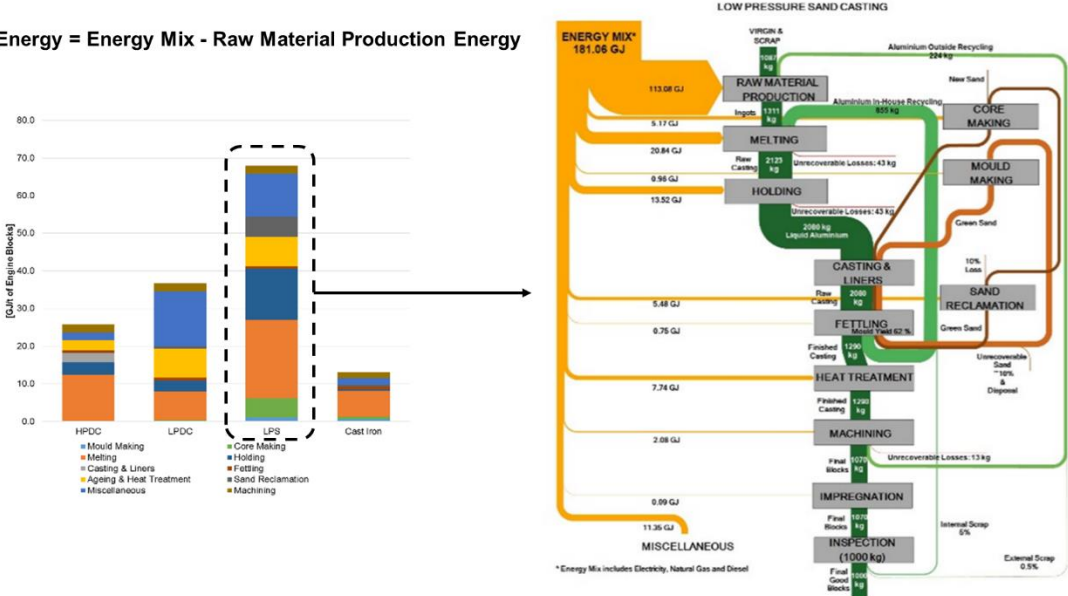
Material and Energy flows

Figure 6: Sankey diagram showing energy and material flows for low pressure sand casting Al cylinder blocks

The visualisation of flows in different forms can assist decision making and exploring the impact of potential improvements. As illustrated in Figure 6, material and energy flows can be effectively represented using Sankey diagrams, illustrating in a clear manner the largest energy inputs, material losses and recycling loops [15]. Such diagrams can be used to assist foundry engineers with decision making and provide them with the ability to perform scenario modelling. The total material and process embodied energies for each manufacturing process investigated are shown in Figure 7.
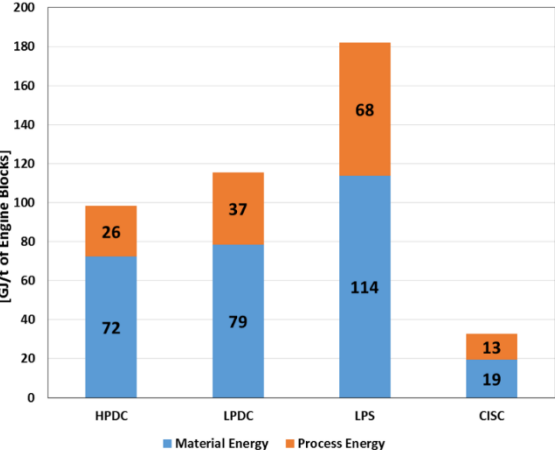

Figure 7: Material and Process Energy/tonne of good castings for the different casting processes examined

Effects of Manufacturing Process Energy Burden on Break Even Driving Distance

In the previous section the material and process energy flow have been recorded for all the manufacturing processes under examination. It is apparent the sand casting of CI is the most efficient process in terms of energy and material consumption. However, in order to look at the big sustainability picture we have to evaluate the Process Energy Burden (PEB) of each casting process on the breakeven driving distance (BED_e). The first step towards this direction would be the estimation of the process energy burden per engine block for each engine block type, namely petrol and diesel, as illustrated in Figure 8.
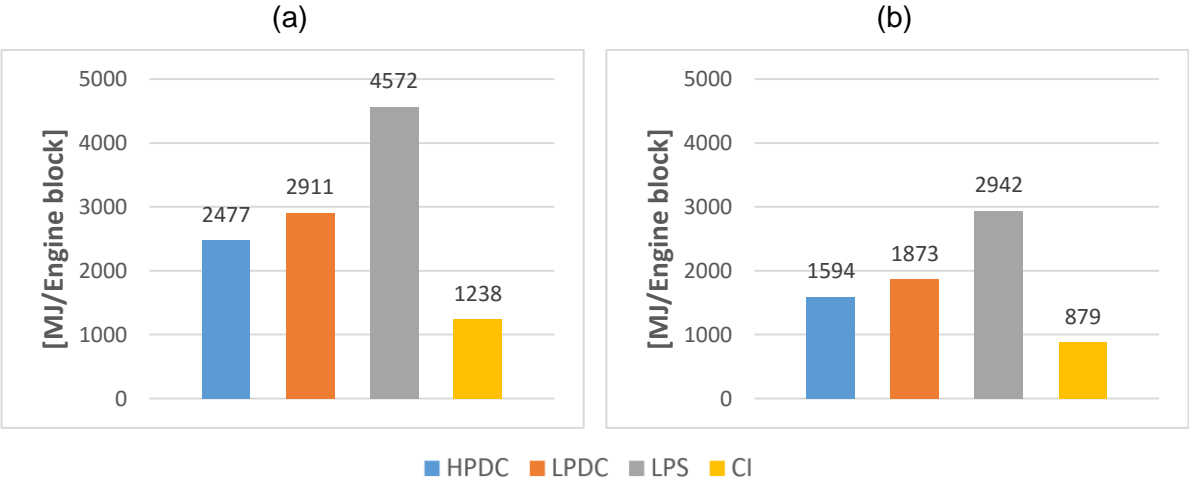
(a)   (b)

Figure 8: Embodied energy per (a) diesel and (b) petrol engine block for each manufacturing process

The next step is to calculate the difference in the Process Energy Burden (ΔPEB) between the lowest energy process (CI) and the rest of the processes. The vehicle mileage for which the fuel savings become greater or equal to the *ΔPEB* is the breakeven driving distance (BED$_e$) and can be estimated according to:

$$BED_e = \frac{\Delta PEB}{(\delta F_s \times E_f \times \Delta M)} \times 10^4 \qquad \text{Eq. 1}$$

where $\delta F_s \left(\frac{L}{100\ km \times 100\ kg}\right)$ are the fuel savings, $E_f \left(\frac{MJ}{L}\right)$ the energy content of the process and $\Delta M\ (kg)$ the engine weight differential. The selected values of the aforementioned parameters based on 4.6% fuel saving for each 10% of weight savings [16] are summarised in Table 1.

Table 1: Values used for break-even calculations based on 4.6% fuel saving for each 10% of weight savings

	Diesel	Petrol
Engine weight differential (kg) (ΔM)	9	7
Fuel savings (L/100km/100kg) (δF$_s$)	0.15	0.20
Energy content (MJ/L) (E$_f$)	38.6	34.2

The breakeven distances of both the Diesel and Petrol engines for various manufacturing processes are shown in Figure 9(a) and (b) respectively. The length of each horizontal line is representative of the variations of savings that can be achieved (6%, 4.6% and 3%). The BED$_e$ results for each weight reduction case considered are also summarised in Table 2**.**

Table 2: Summary of break-even distances (km) for energy (BED$_e$) for different processes and engine block types

Fuel Efficiency savings (%/5-10% weight reduction)	HPDC		LPDC		LPS	
	Diesel	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**
	0.69% Actual weight reduction	0.54% Actual weight reduction	0.69% Actual weight reduction	0.54% Actual weight reduction	0.69% Actual weight reduction	0.54% Actual weight reduction
6% [7]	188,000	115,000	253,000	160,000	505,000	331,000
4.6% [9]	**238,000**	**149,000**	**321,000**	**208,000**	**640,000**	**431,000**
3% [10]	357,000	230,000	482,000	319,000	960,000	663,000

As observed in Figure 9, in a best case scenario a vehicle coming with an Al alloy diesel/petrol engine block has to travel at least 220,000/140,000 km respectively to pay back the additional energy used during its production compared to a vehicle with a CI alloy diesel engine block.
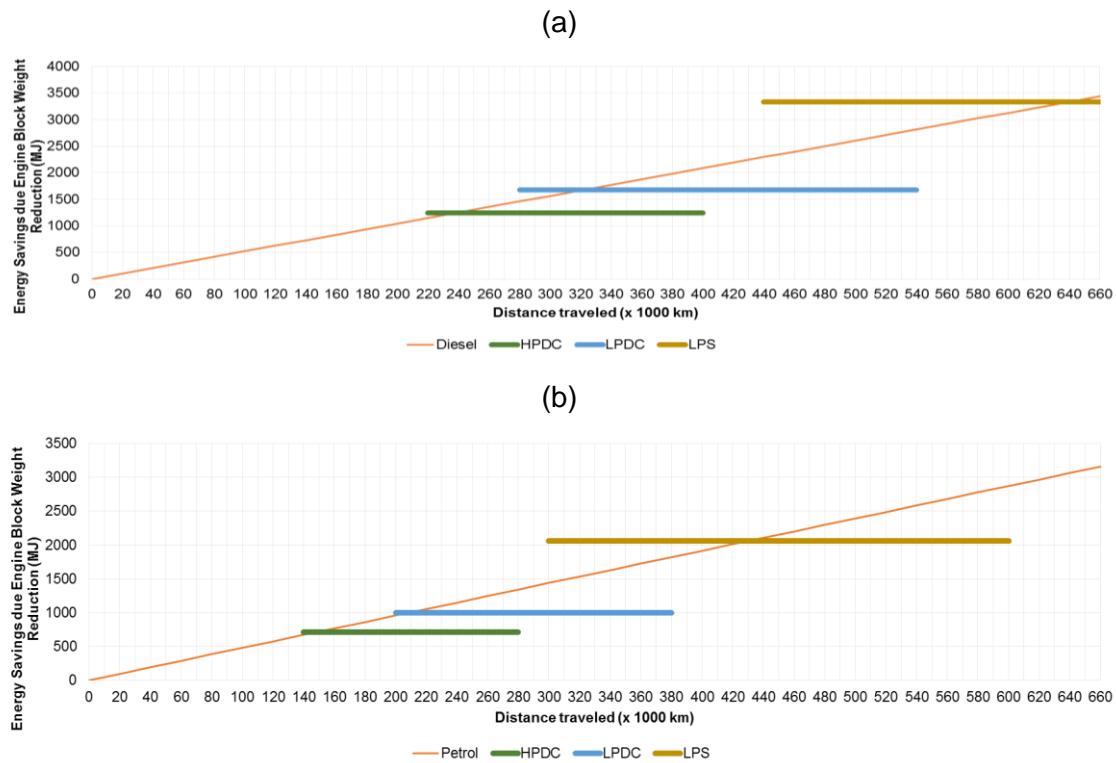
(a)

(b)

Figure 9: Break even driving distance with respect to the embodied energy as a function of the manufacturing process for a (a) Diesel and (b) Petrol engine

Effects of Manufacturing CO_2 emissions on Break Even Driving Distance

The investigation of the CO_2 emissions associated with the manufacturing processes presented above can be considered equally or even more important than their energy efficiency. The source of fuel for producing the energy used in the electrolytic reduction of the Al alloy influences the corresponding CO_2 emissions as illustrated in Table 3**.**

Table 3: CO_2 emissions for different sources of electricity generation [17]

Source	t CO_2/TJ	t CO_2/GWhr
Coal	98.5	355
Gasoline	67.7	244
Hydro	2.5	9
Natural Gas	50.4	181
Nuclear	4.2	15
Oil	69.5	250
Propane	59.9	216
Wind	2.8	10

As a consequence, CO_2 emissions depend on the location in which the primary aluminium is being produced as this is indicative of the sources of the fuel exploited for producing the energy required for the electrolytic reduction. There are a lot of published data on the sources of electricity used for the electrolytic reduction across the world and the corresponding CO_2

emissions ([18], [19]). According to these sources 28% of the electricity used for the production of Al alloys comes from hydroelectric power sources whereas 72% comes from fossil-fuel sources. In addition, CO_2 is also produced from the electrolysis of aluminium for different energy sources according to Table 4.

Table 4: CO_2 emissions produced annually from the primary aluminium production for various energy sources

Energy source	kt CO_2 pa	%
Hydro	2,086	1.2
Coal	158,418	91.1
Oil	65	0.0
Natural Gas	13,149	7.6
Nuclear	181	0.1
Total	173,899	100.0

In order to represent the best possible case for aluminium we considered an infinite recycling loop has been considered and the CO_2 contents have been divided into CO_2 emerging from (a) materials energy and (b) process energy in accordance to the values presented in Figure 7. The energy source for each process has been selected based on the information collected from our survey while the CO_2 footprint of electrical sources of energy has been considered to be equal to 63 kgCO_2/GJ (average world energy CO_2 footprint). The data for the rest of the energy sources has been collected from the Carbon Trust published reports [19]. The CO_2 content emerging from the materials production/process energy is illustrated in Error! Reference source not found., while the CO_2 emissions corresponding to the investigated casting processes are listed in Error! Reference source not found..

Table 5: CO_2 emissions associated with various stages of the examined casting processes

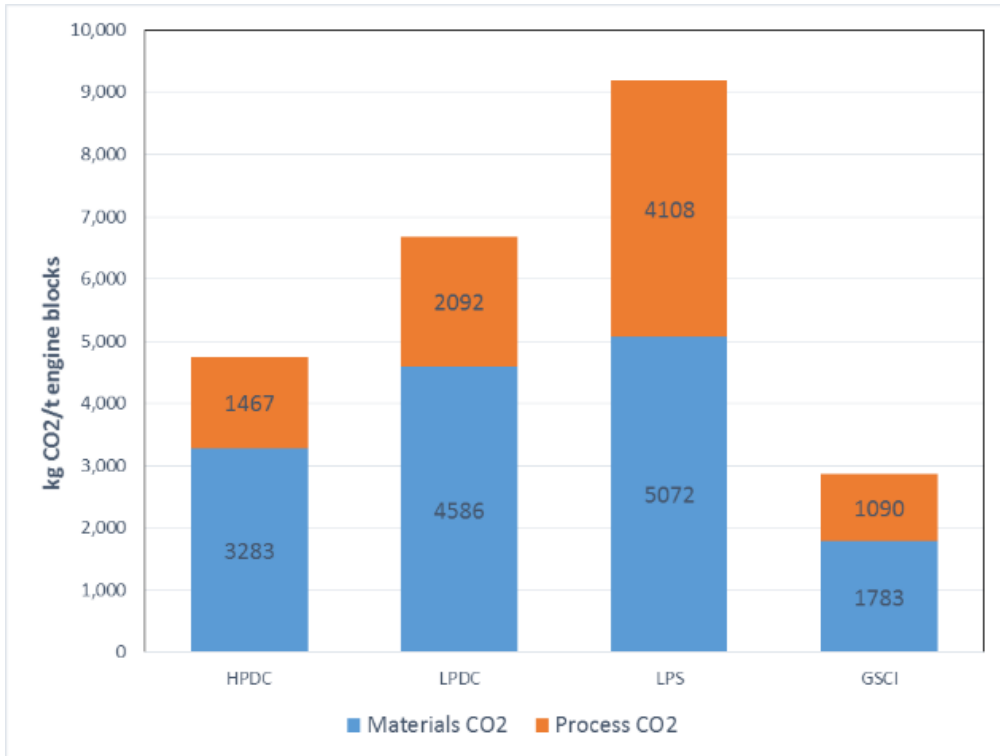| Process	Energy/tonne of blocks cast	Raw materials production	Casting & ancillary processes	Total CO_2 emissions	Difference in CO_2 between Al and CI ΔC	Ancillary Processes
	(GJ/t)	(kg CO_2/t)	(kg CO_2/t)	(kg CO_2/t)	(kg CO_2/t)	%
HPDC	98.2	3283	1467	4750	1876	31%
LPDC	115.4	4586	2092	6678	3805	31%
LPS	181.1	5072	4108	9780	6907	45%
GSCI	32.6	1783	1090	2873	-	38%

Figure 10: CO$_2$ emissions per tonne of good castings for the different casting processes
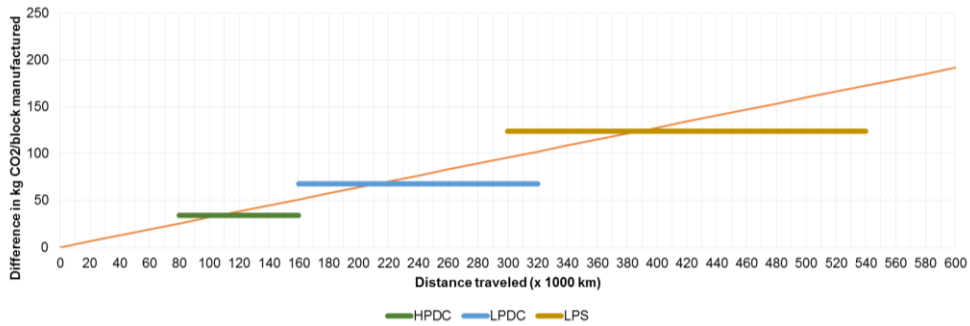
(a)
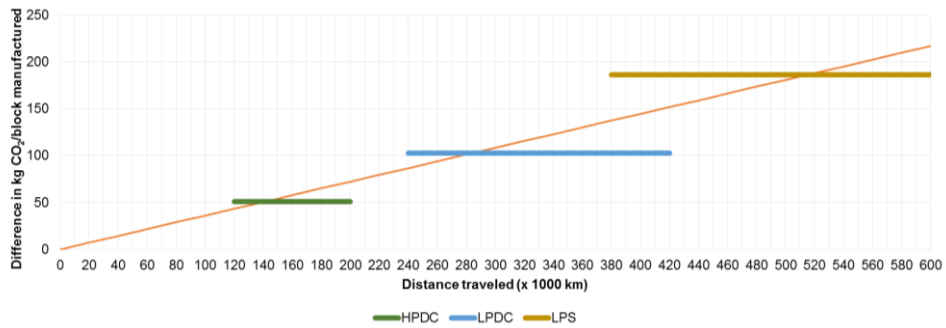
(b)

Figure 11: Break even driving distance with respect to the CO$_2$ emissions as a function of the manufacturing process for a (a) Diesel and (b) Petrol engine

Similarly to the previous section the break-even distance for the CO_2 emissions (BED_c) is defined as the vehicle mileage for which the on-the-road CO_2 emissions corresponding to a specific Al alloy engine block start compensating for the CO_2 emissions generated during its production. According to the results presented in **Error! Reference source not found.**, in a best case scenario a vehicle coming with an Al alloy diesel/petrol engine block has to travel at least 120,000/80,000 km respectively to pay back the CO_2 emissions produced during its production phase compared to a vehicle with a CI alloy diesel engine block.

Benefits of process optimization

According to the results presented in the previous sections, the need for a full assessment of the energy requirements and CO_2 emissions of the "manufacturing" and "use" phases of a component is more than imperative before deciding to substitute currently used materials with so-called lighter ones. Therefore, performing numerical optimization in order to simultaneously maximize the yield of manufacturing processes as well as the quality of the final cast product could be a trustworthy alternative solution [20]. Moreover, decision support tools need to be developed in order to assist design and foundry engineers to select the most appropriate material for a particular application with respect to minimizing the energy requirements and CO_2 emissions of the "manufacturing" and "use" phases of the product. The development of such tools requires the implementation of Artificial Neural Networks (ANNs) and the development of large databases based on the data collected from energy and environmental audits.

Conclusions

Evaluating the effects of substituting conventional materials with lighter ones is a non-trivial process which requires a full assessment of the energy requirements and CO_2 footprint of the "manufacturing" and "use" phases of a component. This investigation is based on data collected from a comprehensive survey of the cast iron and aluminium supply industries to minimize the impact of such assumptions on the energy efficiency and environmental sustainability. According to the results of this investigation, it is evident that on-the-road CO_2 emissions do not adequately reflect the effects of selecting light-weight materials on the environment and energy consumption.

We analysed the data collected from 100 primary sources and given the parameters selected, we concluded that substituting CI products with Al alloy components does not necessarily result in more environmentally friendly vehicles when considering the total energy of manufacturing and actual fuel savings achieved. In fact, in order to compensate for the energy required for the manufacturing process it is necessary to drive a car with an Al alloy cylinder block for at least 120,000 km, depending on the selected manufacturing process. This is

attributed to the high primary energy content in aluminium alloys and the very low weight reduction achieved (< 1% of the total mass of the car).

Based on the reports of the US National Research Council and National Academy of Sciences we found that break-even distances for energy (BED_e) for Al alloy engine blocks are in the range between 185,000 and 560,000 km. As far as CO_2 emissions are considered, break-even distances (BED_c) lie in the range between 106,000 and 471,000 km depending on the manufacturing process selected and percent fuel savings. For some manufacturing scenarios examined, the break-even distances calculated are close to the expected life of a vehicle. However, for most of the manufacturing scenarios, the break-even distances are well beyond the vehicle life.

Other environmental issues are essential to consider when using Al alloys, namely the recyclability of the alloy and the environmental effects of the production of primary aluminium not just on the energy content but also on the waste products, such as the so called "red mud". Current legislation does not adequately account for the full energy content of vehicles or indeed many manufactured products and it behoves legislators and politicians to make justified decisions regarding the use of materials in many applications – not just in transportation.

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