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Article

Life Cycle and Energy Assessment of Automotive Components Manufacturing: the Dilemma Between Aluminium and Cast Iron

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Abstract: Considering the manufacturing of automotive components, there exists a dilemma around the substitution of traditional Cast Iron (CI) with lighter metals. Nowadays, aluminium alloys, being lighter compared to traditional materials, are considered as a more environmentally friendly solution. However, the energy required for the extraction of the primary materials and manufacturing of components is usually not taken into account in this debate. In this study, an extensive literature review has been performed to estimate the overall energy required for the manufacturing of an engine cylinder block using (a) cast iron and (b) aluminium alloys. Moreover, data from over 100 automotive companies, ranging from mining companies to consultancy firms, have been collected in order to support the soundness of this investigation. The environmental impact of the manufacturing of engine blocks made of these materials is presented with respect to the energy burden; the "cradle-to-grave approach" has been implemented to take into account the energy input of each stage of the component lifecycle starting from the resource extraction and reaching to the end-of-life processing stage. Our results indicate that although aluminium components contribute towards reduced fuel consumption during their use phase, the vehicle distance needed to be covered in order to compensate for the up-front energy consumption related to the primary material production and manufacturing phases is very high. Thus, the substitution of traditional materials with lightweight ones in the automotive industry should be very thoughtfully evaluated.

Keywords: manufacturing; energy efficiency; life cycle assessment; aluminium; cast-iron

1. Introduction

Over the years, the material selection for modern car components has changed a lot. As a reference, in the 1970s a design engineer would have to select from four to five sheet forming grades, whereas todays there are more than 50 options [1]. A number of material selection criteria needs to be considered including corrosion and wear resistance, crashworthiness and manufacturability. At the same time, legislation pushes for lighter vehicles, on the basis that lighter cars result in lower fuel consumption. Since 1995 in Europe, the average car CO_2 emissions requirement has dropped from 186 g/km to 161 g/km in 2005 and it is expected to further reduce to 95 g/km in 2021 [2]. For achieving these requirements, automotive manufacturers opt to use aluminium alloys in vehicles for being a "lightweight" material. The average usage of aluminium (Al) in a passenger car varies from 12% to 60% depending on the vehicle. With regards cast Al alloys, these are mostly used for engine blocks, cylinder heads and wheels although they are increasingly used for nodes in the chassis structure and can potentially reduce weight by 40%.

Substituting with lower density materials leads to lower tailpipe emissions; however, this does not consider the CO_2 footprint of the materials used in the manufacturing of vehicles. The CO_2 footprint of any material is related to its embodied energy, which is a synonym of the "track record" of a material and the way it has been produced. In every production phase, energy is needed for changing the phase, geometry and properties of the material. This energy is thus virtually embodied

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in the material. Ashby et al. [3] presented the embodied energy of producing components for the automotive industry and discussed the contribution of each life cycle phase. According to their investigation, the energy involved during the use phase of a vehicle is much larger than that during the material extraction and manufacturing phase. Similar conclusions have been reached by Sorger et al. [4] who investigated the effects of substituting an aluminium cylinder block by a newly developed one made of CI. Their results showed that the CI engine block presents some significant advantages with respect to cost, energy savings and CO_2 emissions.

Manufacturing processes efficiency obviously can have a great impact on the energy consumption during that life cycle phase of the vehicle. Salonitis and Ball [5] highlighted the importance of energy efficiency for both manufacturing processes and systems. One of the most energy consuming manufacturing processes is casting (when considering all sub-processes such as melting, holding, finishing), and a lot of research is undertaken on how to improve its energy efficiency [6–10]. The casting process is used in the automotive sector for the manufacturing of a number of components both in the powertrain and in the body in white. A couple of attempts have been also reported on the use of different materials for the casting of automotive components ([11], [12]).

The objective of the present investigation is to establish a methodology for the environmental impact assessment of substitution of materials in the automotive sector and improve the current decision making practices in the automotive sector. The discussion will be on whether Al alloys are a better option than cast iron (CI), when the total energy burden is considered (and not only the tailpipe emissions). For assessing the energy required, an extensive literature review was undertaken and over 100 experts from the automotive supply chain, such as OEMs, engine design consultancy firms, foundries, mining companies, primary alloy producers and recycling companies, machining, heat treatment and impregnation companies, were contacted. The case study selected is the engine block, as it is the single heaviest component in most passenger cars.

2. Methodology: Assessment Approach

Focusing only on the use phase, or only on the manufacturing phase for the assessment of the overall environmental impact of a product does not allow for a full understanding of the whole picture. The "cradle to grave" approach aims to include the energy consumption that occurs due to resource extraction and processing, component and product assembly, use, and end-of-life processing of a vehicle (Figure 1). The evaluation of the overall impacts that a product has on the environment through all of these lifecycle stages would give a complete picture of the light-weighting shift validity.

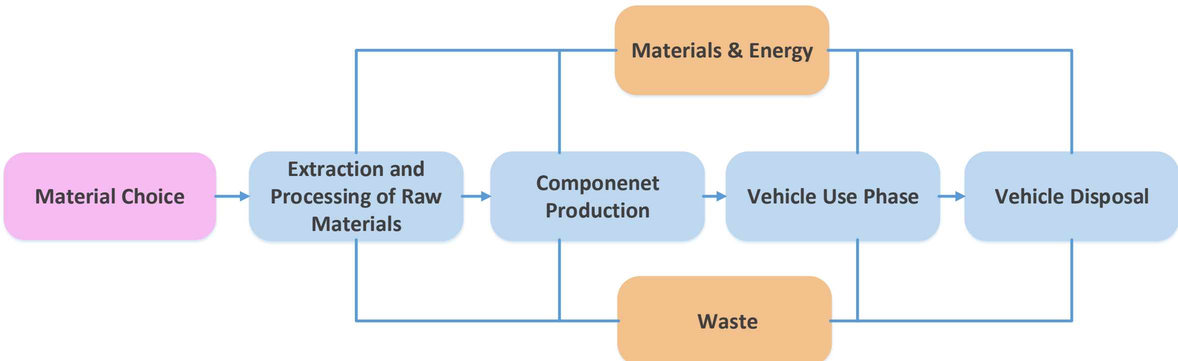

Figure 1: "Cradle to grave" approach

For assessing the energy required and the CO_2 emissions in each stage of the life cycle, an extensive literature review was undertaken. The present study was focused on all the processes, from cradle-to-grave, in the production of passenger vehicle engine blocks, such as mining, smelting and electrolysis, melting, holding, casting, fettling, heat treatment, machining, impregnation and recycling.

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3. Embodied Energy in Materials Due to Primary Production

The starting point is the calculation of the primary production energy for each type of material. For the calculation of embodied energy, the methodology proposed by Brimacombe et al. [13] is used.

3.1. Primary aluminium production

The production of primary aluminium requires a number of steps. Allwood and Cullen [14] suggested that for primary aluminium the energy required is of the order of 170 GJ/tonne. The literature review indicated that energy ranges from 50 to 100 GJ/tonne. Due to the ambiguity in these figures, the energy requirements were calculated theoretically; Figure 2 shows that for 1 tonne of primary aluminium, 98 GJ of energy are required. In the following paragraphs the calculation of these figures is explained.

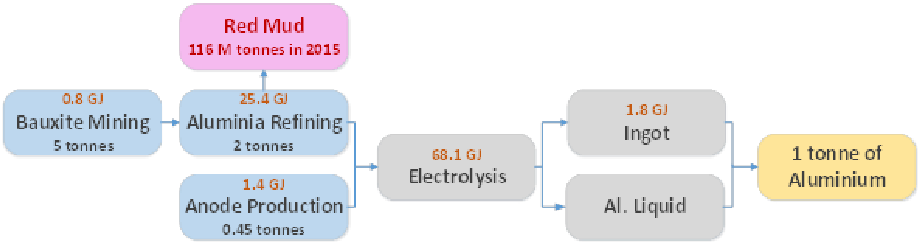

Figure 2: Primary aluminium production steps with associated energy content for producing 1 tonne of material

Primary production of aluminium starts with the mining of dry bauxite, which requires 0.17±0.08 GJ/t. This figure has been calculated after reviewing a number of reported energy figures in the literature review as listed in Table 1.

Table 1: Bauxite mining Energy per tonne of bauxite

Source	Energy [GJ/t]
[15]	0.145
[16]	0.150
[17]	0.150
[18]	0.153
[19]	0.188
[20]	0.210

Alumina is refined from bauxite through the Bayer process, where the main steps are digestion, clarification, precipitation and calcination [21]. First, dry bauxite is crushed in large mills and blended with liquor to form slurry. Then lime and caustic soda are added, mixed and poured into the digester, where a solution of hot caustic soda dissolves the alumina. During the digestion, impurities drop to the bottom and form a solid waste residue called red mud. In order to separate the alumina from the red mud, the mix is moved to clarification. By cooling, aluminium hydroxide is precipitated from the caustic soda and then washed. The last step is calcination, where the water content in hydroxide is removed and the alumina white powder is produced [22]. The energy consumption in this process varies in a range where the calculated average is 13.2±6.4 GJ/t of alumina (Table 2).

Table 2: Alumina Refining Energy per tonne of alumina

Source	Energy [GJ/t]
[19]	13.17
[17]	12.52
[23]	10.65
[15]	12.77
[16]	14.20

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[18]	17.90
[24]	15.00
[25]	13.80
[23]	10.95
[26]	10.65
[20]	13.82

Red mud is highly alkaline (pH=13) having great environmental impact, thus being very difficult to dispose of. It represents a major problem in the primary aluminium production. Red mud disposal covers vast areas which consequently cannot be built or farmed on, even after red mud is dried after several years. The most common ways to dispose of it is by land storage in form of lagoons, dry stacking, or dry cake [23]. Two or more tonnes of red mud are produced for every tonne of aluminium.

The key process for producing Al is electrolysis. Alumina is dissolved in a molten cryolite to decrease the melting point of alumina. The process, known as the Hall-Heroult process after the inventors, passes an electric current through the molten alumina to dissociate it into aluminium and oxygen. The oxygen reacts with the carbon anode to produce CO_2 whilst molten aluminium remains and is tapped off periodically into teapot ladles [22]. In terms of process consumables, carbon anodes are used. A mix of calcined petroleum coke, recycled anodes butts and coal are baked at 1150^{0}C to produce anodes, consuming 3.1 GJ per tonne of anode. Depending on the anode use, the produced Al can be differentiated. The two main technologies are prebake (anodes are baked in ovens and then consumed in the electrolysis cells) and Soderberg (anodes are baked directly in the electrolysis cell) [23]. Furthermore, the carbon anode is totally consumed in Soderberg technologies, while in prebake technologies, 80% is consumed and the other 20 % is used again in the anode production process. In Europe, most of the electrolysis facilities use prebake technology with the only exception of two Soderberg smelters placed in Spain. By calculating the average from the range of energy consumptions required for electrolysis, the process consumes approximately 54.4±4.5 GJ/t of produced Al (Table 3). Also, if 80% of the total amount of carbon anode is converted into carbon dioxide, an extra energy of 14 GJ/t aluminium is added to the process [26] ending up with a total energy consumption of 68 GJ/t aluminium in the electrolysis process.

Table 3: Electrolysis Energy per tonne of aluminium

Sources	Energy [GJ/t]
[27]	56
[24]	52
[28]	66
[21]	54
[29]	53
[16]	55
[20]	47
[23] (95% prebaked and 5% Soderberg)	53.6
[23] (89% prebaked and 11% Soderberg)	55.0
[24]	50
[18]	55
[26]	56

Afterwards, the molten aluminium is poured into moulds to solidify in different shapes, which are shipped as ingots. In some cases, liquid aluminium is transported in insulated ladles by road depending on the proximity of the foundry [18]. The average energy consumption for ingot casting from the range collected from literature review is 1.81±0.17 GJ per tonne of aluminium (Table 4). Finally, by adding up all the energy consumed in all the different processes, the production of one tonne of primary aluminium requires 98 GJ.

Table 4: Cast Ingot. Energy per tonne of aluminium

Sources	Energy [GJ/t]
[26]	2.00
[18]	1.77
[20]	1.67

3.2. Pig Iron production

Similarly, for primary iron/steel the energy required for the production of pig iron, according to the literature review, ranges from 20 to 40 GJ/tonne. Revisiting the process and calculating the energy per phases theoretically indicated that the energy content of 1 tonne of primary iron is 17 GJ (Figure 3). In the following paragraphs the calculation of these figures is explained.

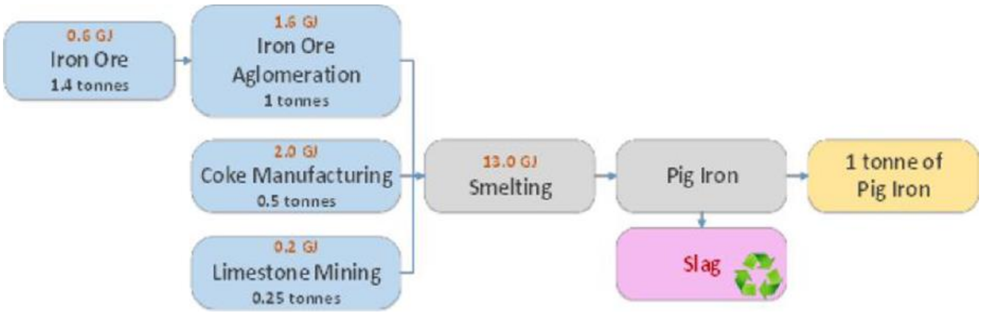

Figure 3: Primary iron production steps with associated energy content for producing 1 tonne of material

According to Moll et al. [30], the main raw material in pig iron production is iron ore, consuming an average energy of 0.44±0.2 GJ/t of iron ore mined (Table 5). Fine iron ores are converted into lump ores before charging into the blast furnace, in a process known as iron ore agglomeration. There are two different processes of agglomeration which are used in industry: sintering and pelletizing. Sintering plants are usually located near the blast furnace site while pelletizing plants are situated near the mines [31]. From the range of data collected, the average energy required for this process is 1.59±0.36 GJ/t of iron agglomerate (Table 6).

Table 5: Iron Ore Mining and concentration energy per tonne of iron ore

Sources	Energy [GJ/t]
[32]	0.153
[33]	0.142
[30]	0.177
[27]	0.956
[34]	0.750

Table 6: Iron Ore agglomeration per tonne of iron ore agglomerated

Sources	Energy [GJ/t]
[35]	1.70
[33]	1.50
[27]	1.37

[36]	1.60
[30] - Pelletizing	1.33
[30]- Sintering	1.55
[37] - Pelletizing	0.82
[37] - Sintering	1.54
[38] - Sintering	2.25
[34] - Sintering	1.75
[31] - Pelletizing	2.10
[31] - Sintering	1.60

Coal is converted at high temperatures to produce coke, which will provide permeability, heat and gases which are required to reduce and melt the iron ore, pellets and sinter [39]. The energy consumed to produce one tonne of coke is approximately 3.98±1.1GJ (Table 7). In some countries like Brazil, charcoal is commonly used in the production of pig iron instead of coke.

Table 7: Coke manufacturing energy per tonne of coke

Sources	Specific country	Energy [GJ/t]
[27]		2.19
[40]		3.70
	Germany 2003	3.70
[34]	Japan 2002	3.50
	China 2004	4.20
[35]		4.30
[37]		4.45
[22]		3.59
[36]		5.80
[38]		2.40
[31]		6.00

Finally, limestone is added in order to remove the impurities [33]. Similar to iron ore, limestone also has to be extracted from the earth, in a process that consumes close to 0.9±0.5GJ per tonne (Table 8).

Table 8: Energy consumption per tonne of limestone

Sources	Energy [GJ/t]
[41]	0.964
[27]	0.848

The iron ore (lump, sinter and/or pellets), along with additives such as limestone and reducing agents (coke) are put into the blast furnace in order to smelt. Then a hot air blast is injected into the blast furnace. The limestone is melted to remove the sulfur and other impurities, originating a residue known as slag. This process, known as smelting, is the most energy consuming in the production of pig iron, accounting for 13 GJ (Table 9) of the total 17.4GJ per tonne of pig iron.

Table 9: Energy consumption per tonne of limestone

Sources	Specifics	Energy [GJ/t]
[22]		16.90
[38]		13.6-16.2
[42]	Blast furnace	12.3

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[40]	Blast furnace	10.4
[27]	Raw iron manufacturing	12.8
[31]	Blast furnace	13-14.1
[43]	Blast furnace	12.7-18.6
[44]		12.0
[34]	blast furnace	10.4
[45]		12.2
[36]	blast furnace	10.4
[37]		13.63

3.3. Outcome

In Figure 4, the various stages and their energy consumption for the production of 1 tonne of pig iron and primary aluminium are shown. The difference in the total energy consumed to produce one tonne of primary aluminium when compared to the production of the same amount of pig iron sums up to roughly 80 GJ.

Furthermore, red mud is a by-product of the primary aluminium production at a rate of 2 tonnes per tonne of aluminium (120 million tonnes per year) and, at this moment, there are no solutions for it. On the other hand, the slag from the smelting process is easily recycled into road and cement making. Finally, electrolysis of alumina consumes 4 times more energy than the whole production of pig iron.

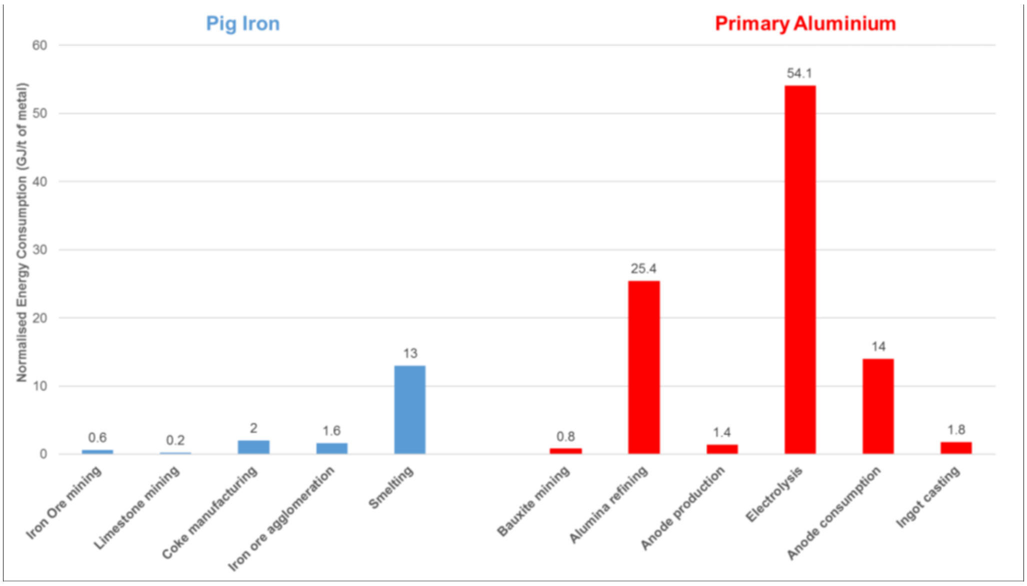

Figure 4: Energy consumption for the production of Pig Iron and Primary aluminium

4. Case study: engine block

The heaviest single component in a passenger vehicle is the cylinder block. Over the last 10 years, the most significant transformation in engines was the capacity to provide more power with a lower displacement. This is a result of one of the most significant engine trends: downsizing. Comparing 2001 with 2013, engine power increased 20% while engine displacement decreased by 10% [46]. Besides that, the top-selling vehicle models worldwide follow this trend. According to [46], the engine displacement of the most sold vehicles is between 0.8 and 2.0L, except for USA and Canada, where engines with more power and displacement are highly valued.

The 4-cylinder blocks were selected as a case study in the present study, as they are approximately 71% of the total blocks manufactured worldwide [47]. For the reasons mentioned in the previous paragraph, the present investigation focuses on in-Line 4 Cylinder 1.6L Engine Blocks. These can be found in both diesel and petrol versions and in both CI and Al alloy materials. Al alloy

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engine blocks are lighter than CI engine blocks as illustrated in Figure 5. However, due to the fact that CI is stronger than Al alloys, Al alloy engine blocks need thicker walls between cylinder bores making them longer. As a result, the volume of CI required is considerably less, being in the region of 55% of that of the equivalent Al alloy block and CI engines are considerably more compact. As illustrated in Figure 5, the weight differentials between the petrol and diesel engines made of Al alloy and CI are 9 and 11 kg respectively. However, more compact engines lead to an even smaller weight difference in the fully assembled engine, as a result of smaller ancillary components. Thus, our calculations are based on an on-the-road weight differential for the engine of 7 kg and 9 kg for petrol and diesel respectively which was substantiated by a number of design consultancy firms and OEMs.

Material	Grey Cast Iron		Aluminium Alloy	
Density (kg/m³)	7850		2700	
Volume (cm³)	3500		7700	
Weight (kg)	Petrol	Diesel	Petrol	Diesel
	27	38	18	27

Figure 5: Weight difference between cast iron and aluminium alloy engine blocks according to the fuel consumed by the vehicle for 1.6L engines

In Figure 6 and Figure 7 the process flow for manufacturing the engine blocks from CI and Al alloys respectively is presented. The key difference between the two process flows is the need for heat treatment in the case of Al alloy engine blocks and the use of liners.

Figure 6: Process flow for CI engine blocks manufacturing

Figure 7: Process flow for Al alloy engine blocks manufacturing

4.1. CI engine blocks

Producing engine blocks from cast iron requires casting to a near net shape and machining to the exact dimensions. For collecting the required data (material use and energy consumption), three casting foundries were visited. These three foundries are responsible for the production of more than 60% of the world's cast iron engine blocks.

4.1.1. Melting stage

The casting temperature for CI and Al vary around 1500°C and 730°C, respectively. This normally occurs in a melting furnace which can differ from foundry to foundry and/or for different metals. Normally, two types of furnaces are used: cupola and induction. By a number of foundries, it was verified that they only use cupola furnaces to produce CI engine blocks. Cupola furnaces use as energy source Coke, and their thermal efficiency ranges between 20 and 30%. The main inputs in these furnaces are pig iron (4.8%), ferrosilicon 75% Si (4%), and steel and/or CI scrap (91.2%). Unrecoverable metal losses, mainly due to oxidation, are reported by foundries, to an average of 2%. In total three CI foundries were audited and the energy per tonne of liquid metal was measured to be 3.9±0.1 GJ (Figure 8).

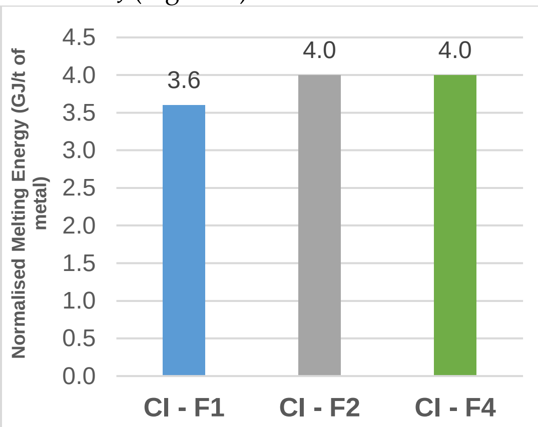

Figure 8: Melting energy per tonne of liquid metal in three different cast iron foundries

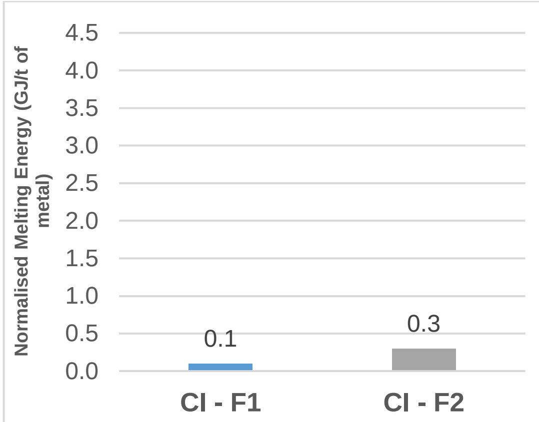

Figure 9: Holding energy per tonne of liquid metal in two different cast iron foundries

4.1.2. Holding Stage

After melting, to keep the metal at casting temperature and with a consistent composition, it is transferred and kept in the holding furnace as a buffer due to different production rates. The energy per tonne of liquid metal was measured to be 0.2±0.1 GJ in two foundries (Figure 9). The holding furnaces in both foundries were electricity powered. One of the biggest factors in the energy consumption during the holding process is the holding time. This changes from foundry to foundry according to the production rate, casting method and of course the type of metal. In the holding process the foundries reported an unrecoverable metal loss of 2%.

4.1.3. Core and mould making stage

In engine block castings, cores are used to form the complex internal geometry of the block. Cores are made from silica sand using the cold box method, where a binder system is used to cure the sand and resin to form the core. The design of the core varies depending on the material to be casted, and for CI engine blocks the reported core weight is 42.6±4 Kg (Figure 10(a)). The process of core making also consumes a significant amount of energy, as the cores are normally coated and baked before use. Three foundries reported average energy needed for core making to be 0.97±0.3 GJ per tonne of core sand (Figure 10 (b)). Further to the cores, a sand mould is used to form the outer limits of the casting. It is also used to support the core package, which together form the core package system. The weight of the sand mould, according to one of the foundries, is approximately 180kg. For the formation of the mould, machining is used that is reported to consume 0.16±0.2 GJ (Figure 10 (c)) per tonne of green sand.

(a) (b) (c)

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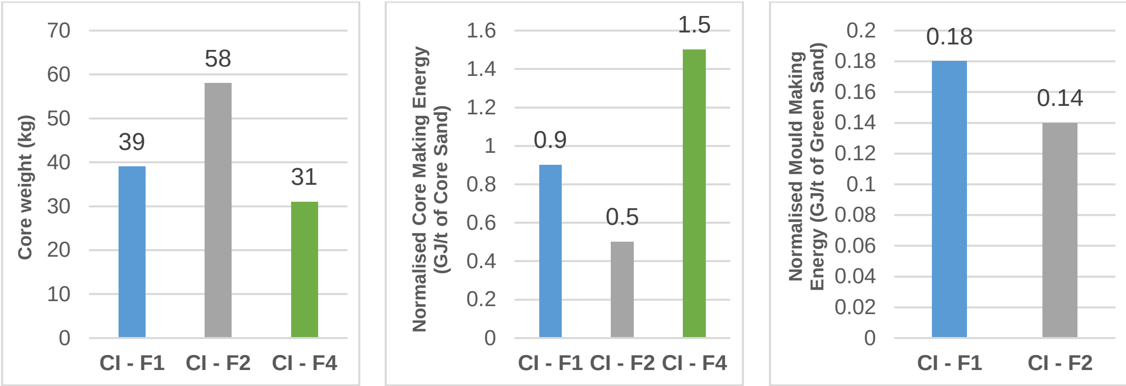

Figure 10: Mould and core making: (a) Core weight, (b) Core making energy and, (c) mould making energy

4.1.4. Casting stage

For the casting of CI into engine blocks, all visited foundries reported that only gravity sand casting is used, using green sand moulds and a core package. In gravity sand casting, liquid metal is poured into a cavity that is formed by a monolithic sand mould, as explained previously. The pouring of the metal can be fully automated, semi-automated or completely manual. Flow rates of the metal may vary from the beginning to the end of a casting campaign as the pouring ladle empties. Metal flow velocities should be adequate to avoid turbulence and achieve a good quality casting. Sand castings have a low cooling rate because of the sand insulating mass surrounding the casting.

4.1.5. Fettling stage

Following the casting process and the removal of the solid block from the sand mould, it has to be roughly machined to remove secondary cavities, risers, runners and gates (also known as fettling). This excess material is usually re-melted. The mould yield reported from all three foundries was 75±1% (Figure 11(a)). The energy consumed during the process varies significantly per foundry, and the reported values range from 0.1 to 1.4 GJ per tonne of liquid metal (Figure 11(b)).

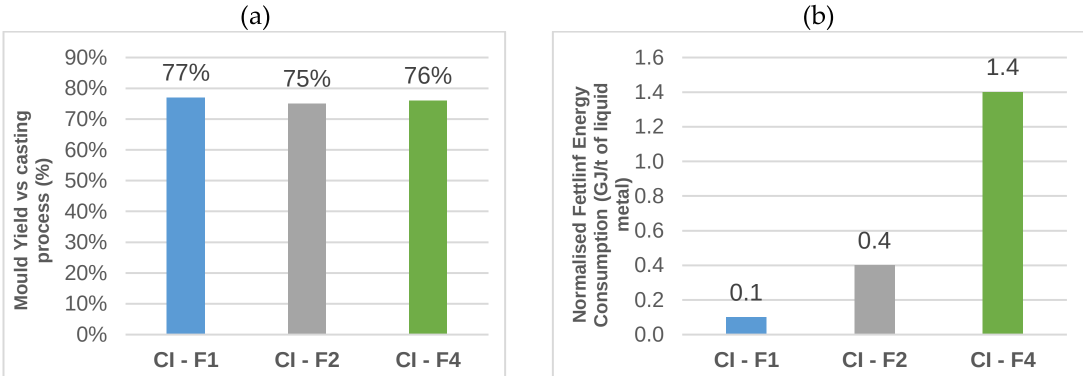

Figure 11: Fettling process: (a) Mould yield in different casting processes (b) Fettling energy consumption

4.1.6. Machining stage

Castings are produced volumetrically larger than required. Surfaces such as cylinder bores, deck face, crankshaft bore etc. are casted with an excess material of 2-3mm that allows later dimensional corrections. A large number of holes must be drilled for oil circulation, bolts etc. The main machining operations in an engine block are cubing, boring, drilling and threading. Machining performance and consequently machining energy consumption may vary according to the machining parameters used. The energy can be significantly reduced by arranging for casting feeders to be located on areas which are to be machined. The approach used to quantify the energy requirements during machining is based on an analytical model provided by MAG Manufacturing Technology [48]. The model used is based on real machining energy measurements and has the capability to aggregate all the ancillary energy requirements (air, coolant supply etc.) into each operation. Cycle times for each operation were obtained from machining outsourcing houses for two in-line 4 cylinder blocks. The total energy consumption calculated for machining one cast-iron block is 61 MJ, i.e. 1.6 GJ/tonne of cast-iron block. Usually 10 kg of material is removed, which represents 20% of the block.

4.1.7. Ancillary processes

Miscellaneous energy is related to the facility operation and other ancillary processes like heating, lighting etc. The energies included in each foundry for the miscellaneous processes vary widely. In the case of the three CI foundries, the reported energy ranged from 0.1 to 3.8 GJ per tonne of good casting.

4.1.8. Inspection stage

Quality inspection is undertaken throughout the casting process. Foundries aim to minimise their internal rejection rate to increase their efficiency by applying strict internal inspection standards in order to not ship and transport bad product. CI foundries reported an average of 3% internal scrap and 0.5% external scrap. Internal scraped CI blocks are re-melted directly.

4.1.9. Materials recycling

In all foundries, material is recycled. The furnace charge that foundries are using for engine block manufacturing comes from two different sources – external recycling (new scrap, old scrap, turnings and dross) and in-house recycling (Figure 12). According to foundry practices, the ratio between the two differs. The dominant production route for steel made from scrap is electric arc furnace while the energy needed equals on average 7 GJ/tonne (Table 10). The most common route for primary steel production is basic oxygen furnace that converts pig iron into steel. The energy for this step on average equals 0.8 GJ/tonne. Together with pig iron production energy, a full steelmaking process equals 18.2 GJ per tonne.

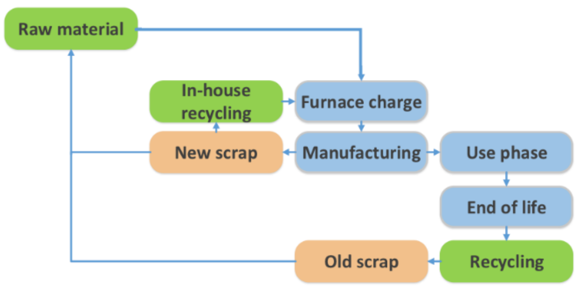

Figure 12: Material flow diagram of the recycling

Table 10: Energy for steel recycling with Electric Arc Furnace

Source	Energy [GJ/t]
World Steel Association, (2015)	5.3 – 8.7
[49]	6 - 15
[50]	8.1 – 9.0
[13]	10
[22]	5.5
[43]	5.3
[44]	5.5

Because the history of the scrap that is used as a furnace charge is not known [13], it is necessary to consider all the stages that the material might go through, from initial manufacture to final

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disposal. Based on the number of product cycles, the embodied energy in the material can be estimated by calculation. The total energy content for the chosen number of cycles can be calculated as follows [13]:

$$X = \left(X_{pr} - X_{re}\right)\left[\frac{(1-r)}{(1-r^n)}\right] + X_{re} \tag{1}$$

According to equation (2), the energy burden for multiple recycling, where the material is recycled indefinitely, can be obtained by calculating [13]:

$$X = X_{pr} - r\left(X_{pr} - X_{re}\right) \tag{2}$$

where X_{pr} stands for energy for manufacturing 1 tonne of material via primary route, X_{re} for the energy for manufacturing 1 tonne of material via recycling route, r is the overall recycling efficiency over one life cycle ($r = RR \cdot Y$), RR is the scrap recovery rate [%] and Y stands for the efficiency of the recycling process [%]. Figure 13 represents embodied energy for steel scrap after recycling. For the Electric Arc Furnace (EAF) route and steel scrap processing, the average overall recycling efficiency (r) includes the furnace yield and the efficiency of recovering the steel at the end-of-life ($r = 0.89$) [13].

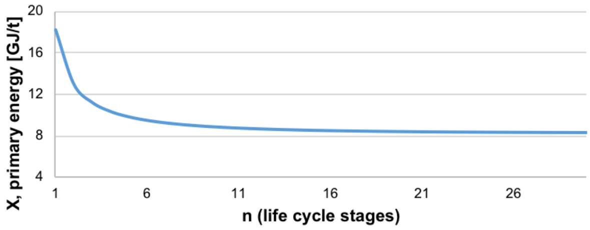

Figure 13: Steel scrap embodied energy (X=8.2) for EAF recycling route

The above analysis though considers only the once-through product system. To undergo a full energy analysis, the influence of recycling and reusing material in the casting process should be also considered [14]. As a result, the multiple life cycle method needs to be adopted. The residue metal that can be again remelted comes from fettling (in a form of runners and feeders), rarely machining (swarf) and internal inspection. Apart from metal, other process materials like core sand and green sand can also be recycled (via thermomechanical or thermal sand reclamation) or reused [51].

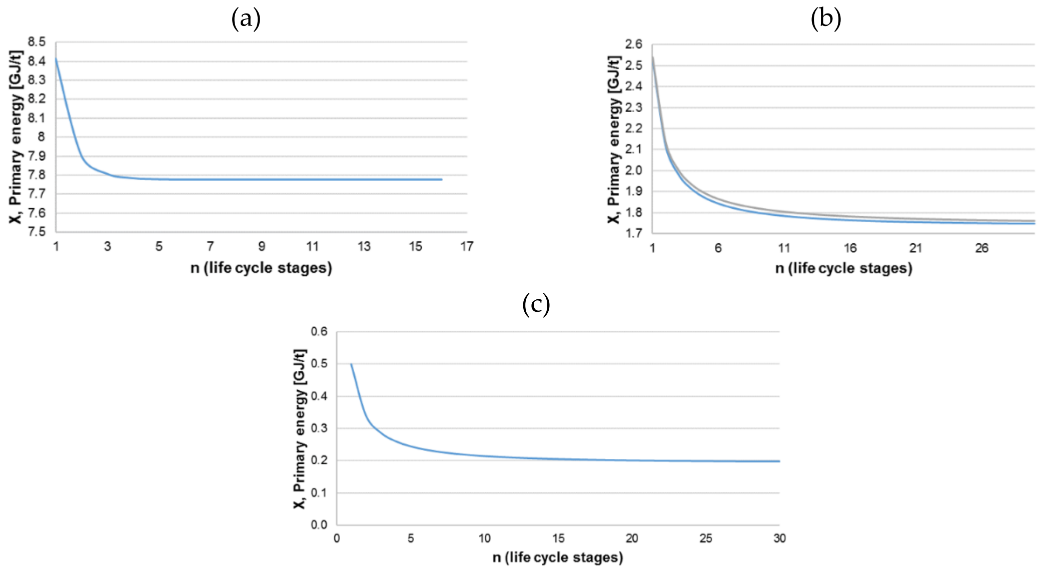

Figure 14: (a) Energy embodied in a metal collected from the production stage and remelted in-house in the cast iron foundries (assumed 2% of the embodied energy for pig iron addition), (b) Energy embodied in a core sand after reclamation process and (c) Energy embodied in a green sand for its multiple reuse

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The alloying and treatment materials need to be considered as well. For CI, ferrosilicon is added to enhance the grain structure and metallurgy of the finished component. The energy content to produce 1 tonne of ferrosilicon master alloy is just over 30 GJ. However, the addition rate into the iron is such that this contributes 1.6 GJ/tonne of CI engine blocks.

Figure 15 shows the Sankey diagram representation of the energy and materials flows. Using this, the largest areas of energy input, recycling loops and material losses are shown.

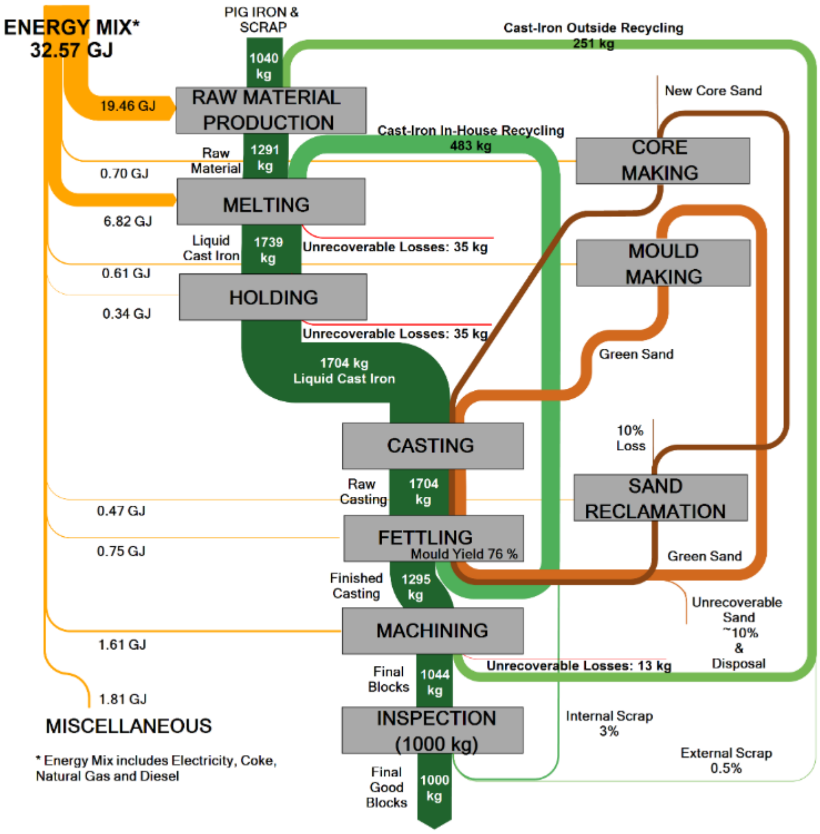

Figure 15: Energy and material flow in CI sand casting, showing that 1000 kg of good castings require the melting of 1739 kg of CI and 32.57 GJ

4.2. Al alloy engine blocks

Figure 7 has shown the process flow for Al alloy engine blocks manufacturing. Compared to CI engine blocks, the process is slightly more complicated, as there is need for use of liners as will be explained later on, as well as heat treatment of the cast components. Furthermore, the casting processes to be used vary from company to company. Three different casting processes can be identified that are widely used for the manufacturing, namely high pressure die casting (HPDC), low pressure die casting (LPDC) and low-pressure sand casting (LPSC - also known as Cosworth process). 70% of aluminium alloy engine blocks are casted by HPDC while the other 30% are casted through the other methods together [23].

The LPDC process consists of a dosing furnace which is pressurized forcing liquid aluminium to enter the mould from the bottom. The mould consists of steel dies combined with internal sand cores. The repeatable raising and falling of the metal through the delivery tube may introduce oxide layers which eventually are delivered to the casting. LPDC is used for medium to long series casting runs, where better mechanical properties are required when comparing to HPDC. In HPDC, the alloy is inserted into a cold chamber and a hydraulic piston squeezes the metal into a steel die mould at extremely high speed (up to 80 m/s) and pressure (3500 tonnes). No sand cores could withstand the high pressure so the HPDC block designs are limited to open-deck blocks.

Similar to cast iron green sand casting, aluminium gravity sand casting also uses core packages. In the LPSC (Cosworth process), the metal is usually pumped into the sand mould from the bottom

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by an electrical pump. The difference from LPDC is that the metal in the pump never drops back to the level of the metal and consequently the level of oxide generated is potentially lower than in a gravity system [52]. Data were collected from a number of foundries that employ such processes.

4.2.1. Melting and holding

In Al alloy engine block foundries, tower furnaces are most commonly used [6]. The unrecoverable metal losses are in the same order of magnitude as CI. The foundries contacted reported average energy consumption of 6.5±3 GJ per tonne of liquid metal (Figure 16). With regards to the holding of the liquid metal, the holding time varies between foundries. In HPDC and LPDC the holding time is around 4 hours while for LPSC it is 13 hours because of the additional time required for refining of the metal. The foundry using the Cosworth process, used holding as a refining step to allow unwanted trace element to settle out of the liquid Al alloy and oxides to float to the surface. Figure 17 shows the holding energy in GJ per tonne of liquid metal.

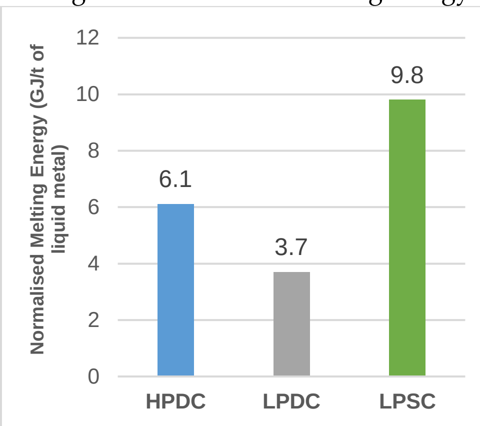

Figure 16: Melting energy per tonne of liquid metal in three different Al foundries

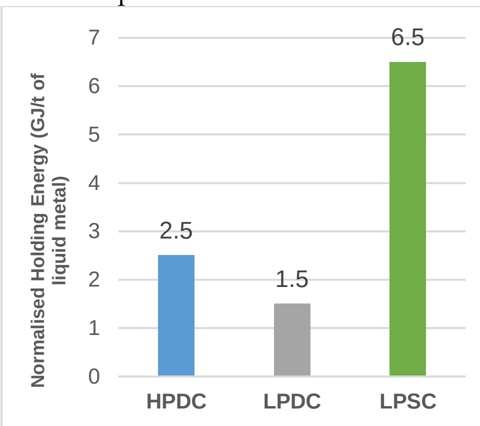

Figure 17: Holding energy per tonne of liquid metal in three different Al foundries

4.2.2. Core and mold making

The material and the process used for the core and mold making depends on the type of the casting process to be used. In LPSC foundries, cores are made from silica sand using the cold box method, where a binder system is used to cure the sand and resin to form the core. In HPDC sand cores are not used due to the high-pressure injection of the metal which would destroy the cores. The core weight also varies for the different metals. The cores in cast iron sand casting are much heavier than aluminium LPDC. This is because it includes the whole core package (cores + core shells). The energy required for making cores and the mould is quite similar with cast iron sand casting (CISC), with the exception when dies are used.

4.2.3. Casting

The four different casting processes have been presented already. As per CI, the energy consumed during the casting process is negligible with the exception of HPDC. In HPDC, automatic spray up for lubrication and robotic casting removal after solidification also consume a lot of energy. The dies are usually monolithic and contain cooling and heating channels. Due to these extra energies in HPDC, a casting energy is accounted only for this casting method (1.2 GJ per tonne of casting). HPDC parts are near net shape and less fettling and machining operations are required. Due to the nature of metal filling, HPDC castings are often non-heat treatable but might go through a stress relieving thermal cycle.

4.2.4. Fettling

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Once the cast engine block is removed from the sand mould or the die, fettling is required as per CI process as well. In the case of Al-alloy engine blocks, the reported mould yield is lower compared to CI and is approximately 65±2%. The material removed from fettling aluminium alloy engine blocks can be remelted directly in the foundry or sold to an external recycling company to be transformed again in aluminium alloys. The second case relates to aluminium LPDC and therefore, the calculations in this study, for LPSC, are based on outside recycling. The energy consumed during the fettling process was reported in all three foundries to be 0.6 GJ per tonne of liquid metal.

4.2.5. Heat treatment

A key difference in the CI process flow is the need for heat treatment. Al-Si alloys used to produce Al alloy engine blocks usually require T6 and T7 heat treatments which are used to improve both mechanical and wear properties [53]. Foundries also reported that T5 is the most common heat treatment process used in HPDC. The average energy consumption per casting can be calculated when temperature and holding times are known.

Considering a treatment efficiency of 100%, the average energy consumption for heat treatments T6 and T7 can be calculated to be 3.2 GJ/tonne of finished casting. For T5, the average energy consumption is calculated to be 1.0 GJ/t. For the case of engine blocks casting, 20% heat treatment efficiency is required, thus the values considered were scaled accordingly.

4.2.6. Impregnation

Casting introduces porosities during the solidification of the liquid metal. Turbulent metal flow, gas entrapment and metal shrinkage are the main factors that introduce voids in the casting. Porosity is more pronounced in aluminium alloy castings because of its higher volumetric shrinkage and hydrogen content. The three main forms of porosity are full enclosed, blind and through porosity. Such porosity could result in leaking under pressure, and would thus require the block to be scrapped. Impregnation process that introduces a polymer sealant in the pores and cracks of castings is used for this reason. The most commonly used impregnation process is the vacuum dry process. The castings are stashed into a basket and inserted in a series of chambers until a full impregnation cycle is achieved.

Around 90% of the energy in an impregnation cycle is consumed heating up the water at around 90°C and the rest 10% for circulation pumps, vacuum pumps, rotational mechanisms and other ancillary systems. The energy involved in the process was ascertained to be around 7.2MJ/engine block.

4.2.7. Machining

Using the MAG analytical model [48], the total energy consumption for machining is 51 MJ, of which 13 MJ is for the initial machining of the cylinder liners.

4.2.8. Liners casting

For the aluminium alloy in-line 4 cylinder blocks, for all casting processes, cast-iron cylinder liners are cast in the block. The wear and mechanical properties of hypoeutectic alloy sliding surfaces are not adequate to withstand the friction of the moving piston in the cylinder bore. Cast-in CI liners are used for the tribological system “cylinder-piston-piston ring”. The liners are centrifugally cast and the induction pre-heated prior to casting at around 375°C to achieve better bonding with the liquid Al ending up with a total energy of 188 MJ/engine block. For the fettling of the solid casting system, the yield ratio is approximately 67% with a total energy consumption of 0.6 GJ per tonne of liquid metal.

4.2.9. Materials recycling

As with the CI foundries, Al foundries are charging their furnaces with recycled material as well. The process is quite similar, however Figure 12 needs to be updated in order to include secondary

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smelter and production of ingots. Figure 18 illustrates the common processes for the material flow of the recycling model for the case of Al-alloys.

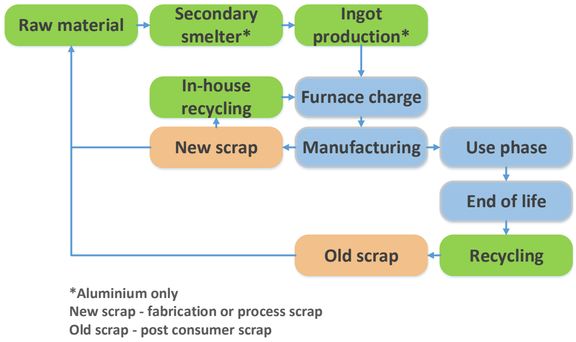

Figure 18: Material flow diagram of the recycling

Al alloy engine blocks are usually made from secondary ingot. The alloy used is A383 or A380 for LPDC and HPDC and A319 for LPSC. The process of recycling Al scrap to form the alloys is by refining, a process that uses a combination of rotary and reverberatory furnaces [54]. The recycled Al can have similar properties to primary Al. However, in a course of multiple recycling, more and more alloying elements are introduced into the metal cycle. Secondary alloys have relatively high levels of impurities, especially iron, that is detrimental to many properties. The multiple life cycle method is thus used (as in the CI recycling) for calculating an average energy consumption.

Figure 19, Figure 20 and Figure 21 present the Sankey diagrams for the LPSC, LPDC and HPDC cases respectively.

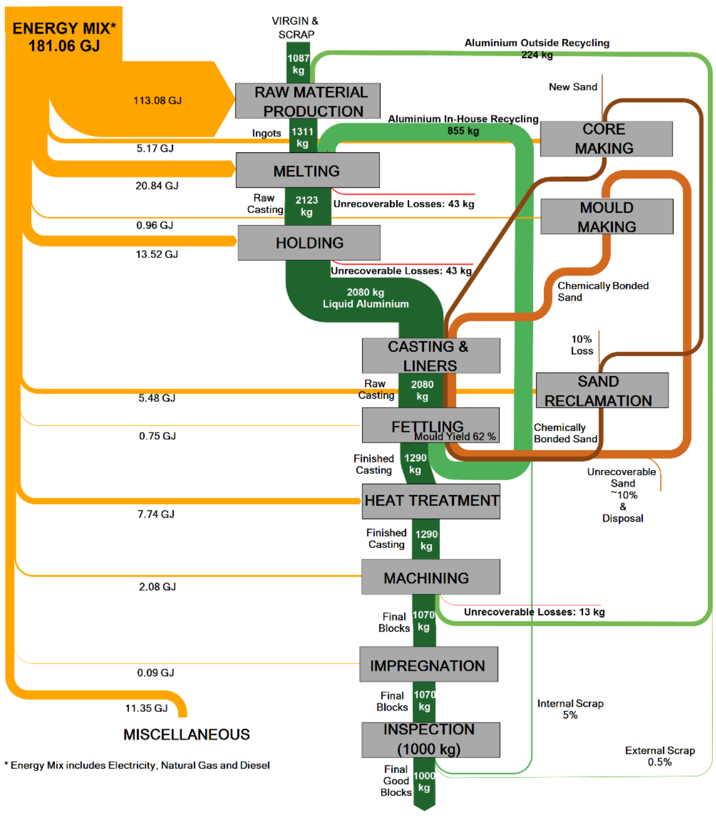

Figure 19: Energy and material flow in LPSC, showing that 1000kg of good castings requires the melting of 2123 kg of Al and 181.06 GJ

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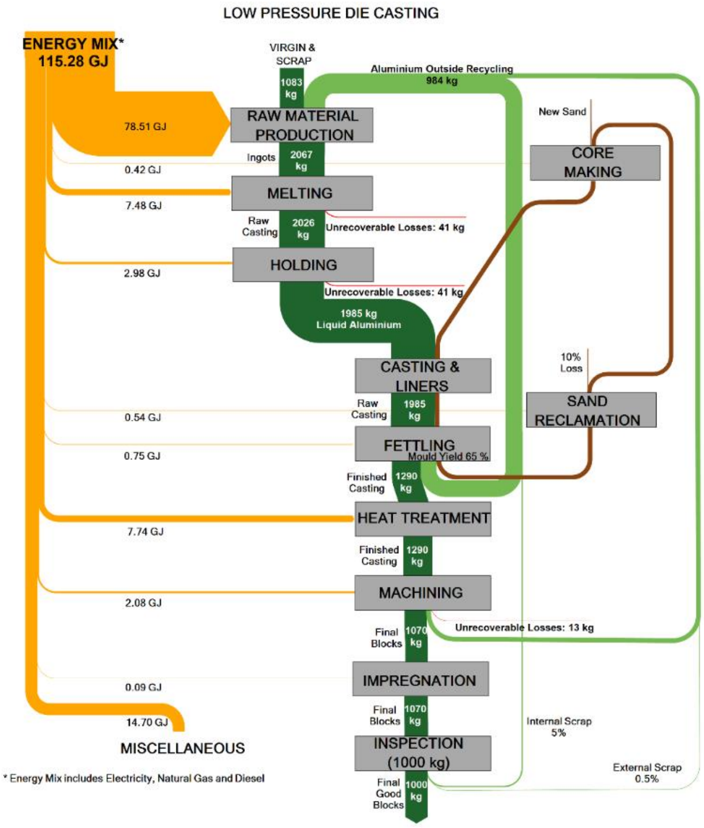

Figure 20: Energy and material flow in LPDC, showing that 1000kg of good castings requires the melting of 2067 kg of Al and 115.28 GJ

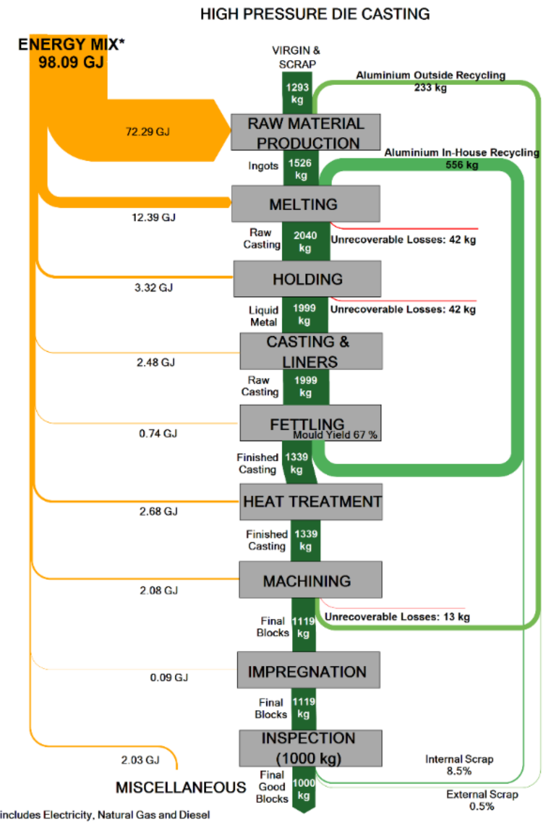

Figure 21: Energy and material flow in HPDC, showing that 1000kg of good castings requires the melting of 2040 kg of Al and 98.09 GJ

5. The Answer to the Dilemma Between Al Alloys and CI

Figure 22 shows the energy breakdown in each material source and indicates that ingot and external scrap represent the highest embodied energy of the charge and feedstock for Al alloy and CI engine blocks. Figure 23 demonstrates the process energy breakdown for each casting. It is obvious that the CI engine block requires considerably less energy. The excess energy spent for the manufacturing of Al alloy engine blocks, should be compensated by the fact that the vehicle is lighter and thus consumes less energy during its use.

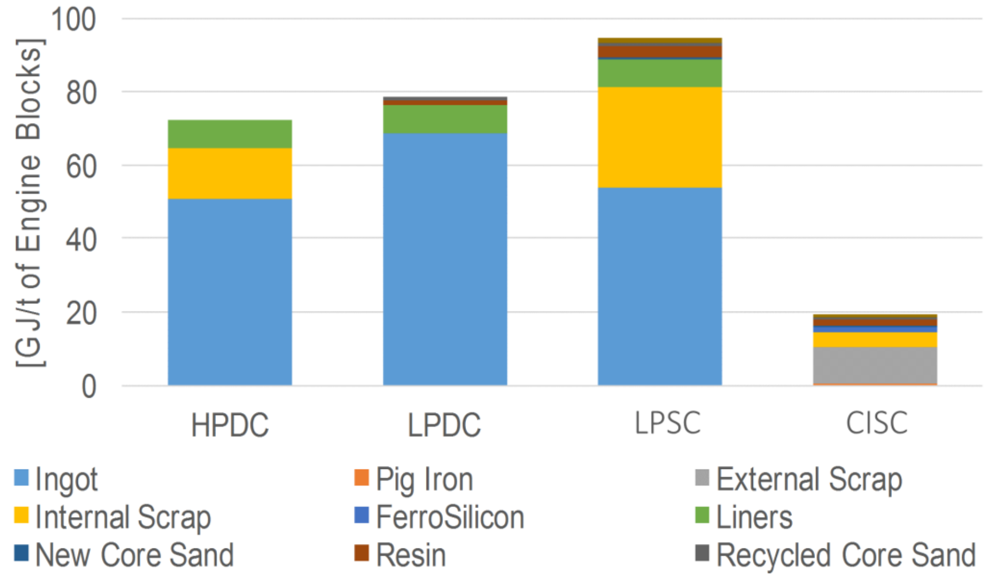

Figure 22: Embodied material energy per tonne of engine blocks

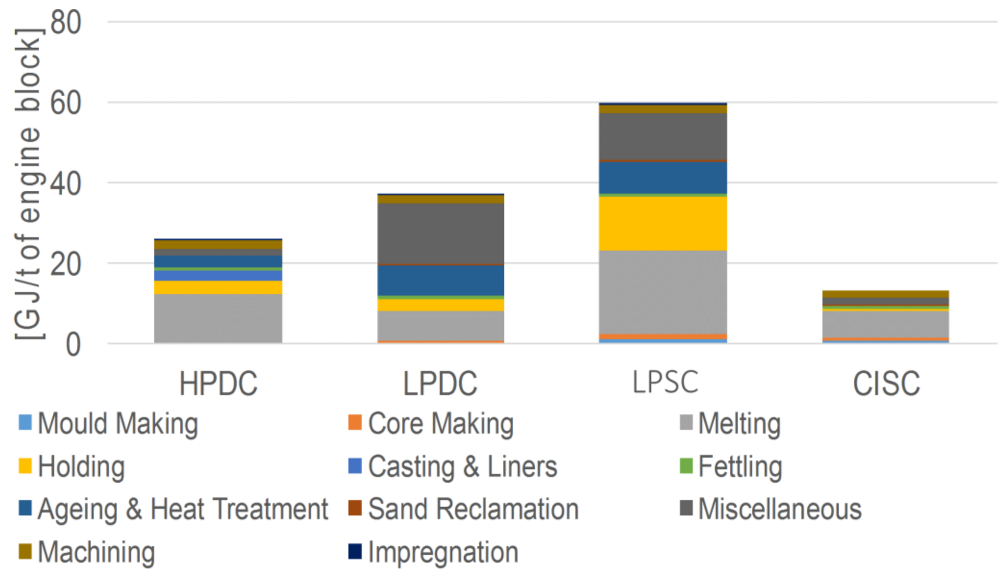

Figure 23: Process energy per tonne of engine blocks

Figure 22 and Figure 23 provide information about the embodied and process energy per tonne of engine block. However, it is equally significant to represent the data above using a single block as a functional unit. The process, embodied and total energy, which is equal to the sum of the embodied and process energy, required for the production of each single engine block via the 4 manufacturing processes, are listed in Table 11.

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Table 11: Total energy per engine block

	HPDC		LPDC		LPSC		CISC	
	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Process Energy (GJ/t)	25.8	25.8	36.78	36.78	59.12	59.12	13.11	13.11
Embodied Energy (GJ/t)	72.37	72.37	78.63	78.63	114	114	19.46	19.46
Weight of single block (kg)	27	18	27	18	27	18	38	27
Process Energy (GJ/block)	0.64	0.41	0.91	0.58	1.46	0.93	0.5	0.35
Embodied Energy (GJ/block)	1.79	1.14	1.94	1.24	2.81	1.79	0.74	0.53
Total Energy (GJ/block)	2.43	1.54	2.85	1.81	4.28	2.72	1.24	0.88

The embodied energy due to manufacturing and use is illustrated in Figure 24 (shown for the case of diesel engines, similar results were attained for petrol engines). The starting values of the embodied energy correspond to the total energy of the manufacturing process (Table 11). It is evident that the vehicle would have to be driven more in order for the light-weighting benefit. This is due to the much higher embodied energy of Al alloys compared with CI as a result of the huge energy content during both the electrolysis and bauxite conversion stages of the production of aluminium.

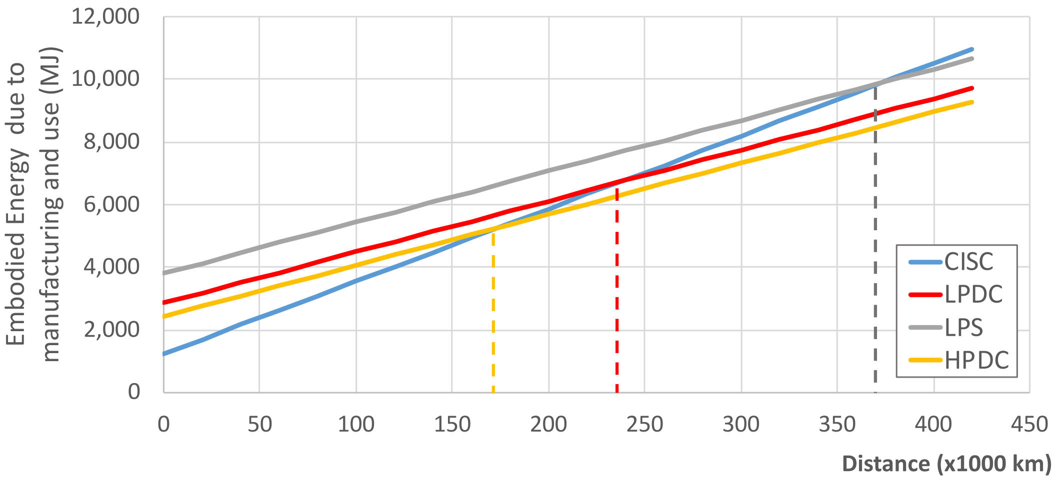

Figure 24: Breakeven distance for paying back the lightweight material (for a diesel automotive vehicle of 1200kgr with average consumption of 7l/100km)

Table 12: Parameters for the BED calculation

	Diesel	Petrol
$\delta F_s \left(\frac{L}{100\ km \times 100\ kg}\right)$	0.2	0.25
$E_f \left(\frac{MJ}{L}\right)$	38.6	34.2
$\Delta M (kg)$	9	7

The distance needed to be covered by a vehicle in order to compensate for the additional energy due the manufacturing and primary production of their engine block is estimated using the breakeven distance (BED) according to:

$$BED = \frac{\Delta PEB}{(\delta F_s \cdot E_f \cdot \Delta M)} \cdot 10^4 \qquad (3)$$

where $\Delta PEB\ (MJ)$ is the difference in the process energy burden between the manufacturing process with the lowest total Energy (CISC) and the rest of the processes, δF_s are the fuel savings, E_f the energy content of the fuel and ΔM the engine block weight differential (Table 12). The values of the breakeven distance for the two types of engine blocks (diesel and petrol) and the various manufacturing processes under examination are summarised in Table 13.

Table 13: BED (km) vs CISC for various types of engine blocks and manufacturing processes

	Diesel	Petrol
HPDC	170,889	110,611
LPDC	232,141	155,809
LPSC	369,221	256,960

6. Conclusions

Nowadays, the legislation around the automotive industry is focused on the reduction of the tailpipe emissions of the vehicles and does not consider the production phase of automotive components. Automotive companies are compelled to pursue a light-weighting and engine downsizing design strategy to comply with the steadily more stringent targets in emission standards. The objective of this investigation is to perform a thorough lifecycle analysis of an automotive component (engine block) made of two different materials, CI and alloy respectively, in order to review the potential energy savings of light-weighting.

The “cradle-to-grave” approach was adopted to calculate the overall energy requirements, including the energies for the production of the raw materials, while acknowledging the embodied energy from the initial manufacture up to the final disposal. Our results indicate that the energy required for the primary production and manufacture of CI engine blocks is much lower compared to the Al alloy engine case. On the other hand, Al alloy blocks are more lightweight and contribute to the increase of the fuel savings during the use phase of the particular component.

In order to evaluate the effects of light-weighting on the overall energy consumption during the component’s lifecycle, the weighted average breakeven distance (required to compensate the extra energy consumption in Al alloy engine blocks) was estimated and found to be around 175,000 km. The breakeven distance fluctuated between 175,000 to 370,000 km for a diesel and 115,000 km to 260,000 km for a petrol engine block respectively. The conclusion drawn is that, comparing to an average passenger vehicle life of 200,000 km, for the LPDC and LPSC processes the vehicle will never recover the extra energy in the Al alloy engine blocks while being on-the-road. Therefore, the substitution of materials, traditionally used in the automotive industry, with lighter ones should be very carefully considered.

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