Cast Iron or Aluminium: Which Cylinder Block Material is best for the Environment?

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Introduction

Emissions legislation in the automotive industry focusses entirely on tailpipe emissions, with no consideration for the CO_2 footprint of the materials used to manufacture the vehicle. This legislative mandate has led many OEMs to adopt aluminium cylinder blocks, in order to reduce weight, fuel consumption and tailpipe CO_2 emissions. However, the production of aluminium consumes significantly more energy than cast iron – both during primary manufacturing and in the foundry.

To determine if the use of aluminium provides a net benefit to the environment, the Sustainable Manufacturing Systems Centre at Cranfield University in the United Kingdom conducted a comprehensive study to quantify the life cycle energy and CO_2 impact associated with the production of diesel and petrol engines. The study included interviews with more than 100 industry experts from OEMs, engine design consultancy firms, cast iron and aluminium foundries, heat treatment facilities, raw material and recycling suppliers, and machining companies across the western world.

Using established life cycle methodologies, the research focussed on the base-case of a 1.6 litre four-cylinder engine with an 86 mm bore diameter and a deep-skirt cylinder block. For the aluminium cylinder blocks, three different foundry manufacturing processes were evaluated: high pressure die casting (HPDC); low pressure die casting (LPDC); and, low pressure sand casting in a complete core package (LPS). The aluminium cylinder blocks incorporated cast-in grey iron cylinder liners with a weight of 1.75 kg per set of four liners, after final machining. The cast iron cylinder block was produced in conventional grey iron with a tensile strength of 250 MPa, in a complete core package contained within a green sand mould. The cylinder block weights adopted in this study are shown in Table I. These values were based on the results of the industry surveys and benchmarking of current series production engines. Care was taken to focus on passenger vehicle engines, to account for the fact that aluminium is often used for passenger vehicles while cast iron engines of the same displacement are often used for heavier-duty work van applications.

Table I:
Fully machined mass (kg) for 1.6 litre cast iron and aluminium cylinder blocks

Diesel			Petrol		
Aluminium*	Cast Iron	Difference	Aluminium*	Cast Iron	Difference
27	38	11	18	27	9

**Note: includes 1.75 kg for cast-in grey iron cylinder liners*

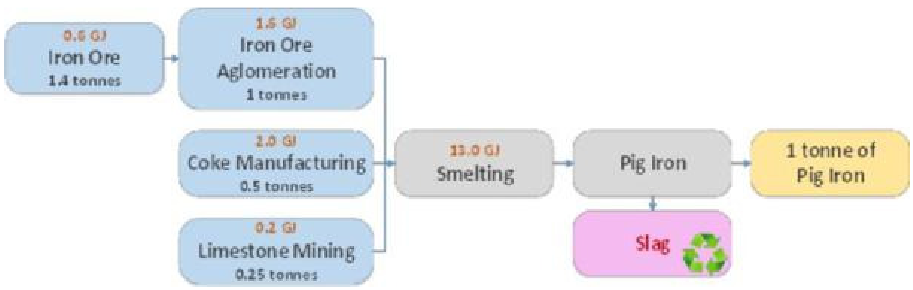
Due to the higher strength and stiffness of cast iron, and the absence of cylinder liners, cast iron cylinder blocks can be shorter than aluminium cylinder blocks of the same displacement. This allows for secondary reductions in the size and weight of the ancillary components that traverse the length of the engine. Ultimately, the on-the-road mass increase for cast iron was defined as 7 kg for the petrol engine and 9 kg for the diesel engine. The total vehicle mass was fixed at 1,300 kg, resulting in 0.54% weight reduction for the petrol engine and 0.69% weight reduction for the diesel engine compared to the same vehicle with and aluminium cylinder block.

In the on-the-road use phase, the present study applied a payback fuel saving of 4.6% for every 5-10% of vehicle weight reduction. This value was chosen because it was adopted for the 2017 EPA midterm fuel economy review in the United States [1]. Other reports have advocated fuel savings ranging from approximately 3% up to 6%. Therefore, the breakeven calculations were conducted for fuel savings of 3%, 4.6% and 6% savings for each 5-10% of weight saving to provide a sensitivity analysis beyond the 4.6% base-case.

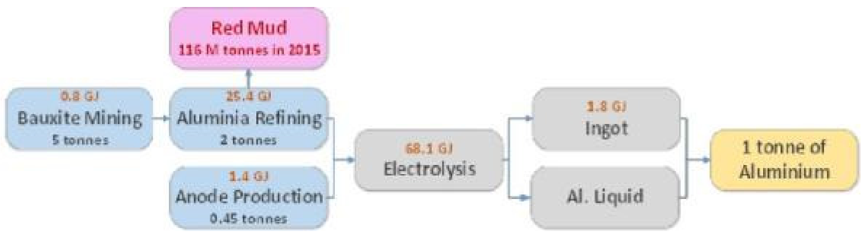
Raw Material Embodied Energy

The embodied energy is defined as the energy contained in the raw materials needed to produce a component. For the case of a cylinder block, this includes the virgin metal, the recycled metal, the alloying elements, and the mould and core sand and binders. In the case of the aluminium cylinder block, it also includes the cast iron used for the cast-in cylinder liners. For both iron and aluminium, all alloying elements greater than 1% were included in the analysis. Infinite recycling was assumed to provide the best-case scenario for the amortisation of the energy used in the production of the primary metal.

The material energy begins with the energy required to mine, process and convert the mineral ores to primary metal. Figure 1 summarises the individual steps and shows the typical energy consumption associated with each step. The energy results were determined from production data provided by primary metal manufacturers and from information published in the public domain. Figure 1(a) shows that the production of one tonne of pig iron from a blast furnace requires approximately 17 GJ (125 GJ/m^3) while Figure 1(b) shows that the energy required to produce one tonne of primary aluminium is approximately 98 GJ (265 GJ/m^3). These primary energy contents have been applied in the correct proportions to account for the embodied energy when primary materials are used in the foundry process, either as pig iron in cast iron production or as 'sweetener' in aluminium recycling. Figure 1 also reflects the by-product streams for each process. The blast furnace slag generated during pig iron production is typically recycled and used as aggregate in the construction industry. During alumina refining, two tonnes of red mud are generated for every tonne of primary aluminium. The red mud has a pH value of 13 and must be landfilled.



(a) Primary iron production



(b) Primary aluminium production

Figure 1: Process steps and associated energy contents to produce one tonne of primary metal

The cast iron and the aluminium foundry industries predominantly use recycled metal as the charge materials. It is estimated that the cast iron foundry companies evaluated in this study account for more than 75% of the cast iron cylinder blocks produced in Europe and the Americas. These foundries all used cupola melting. Although cupola melting has a higher energy consumption and CO_2 footprint than induction melting, it is favoured by the larger foundries due to the higher production rates. For cast iron, an average charge make-up of 91% recycled material and 9% pig iron was used for the energy analysis. The recycled material had an energy content of 4 GJ/t for in-house recycling (gating systems) and 10 GJ/t for external scrap (steel scrap, end of life cast iron components, machining chips). The only alloying elements greater than 1% in cast iron are carbon and silicon. The carbon is primarily provided by the coal-based fuel for the cupola furnaces, while ferrosilicon is added separately to raise the silicon content to 2.2%. The energy required to produce ferrosilicon is rather high (30 GJ/t), but due to the small addition rate, the incremental energy addition equates to 1.6 GJ per tonne of cast iron cylinder blocks.

It is estimated that the aluminium foundries evaluated in this study represent more than 50% of the aluminium cylinder block production in Europe and the Americas. The foundries used significantly different charge materials, depending on the casting process. The HPDC foundries used approximately 27% internal scrap added to A380/383 secondary foundry ingot. The LPDC foundry used 100% primary A356 foundry ingot, with no in-house recycling (all processing was conducted by an external recycler). The LPS foundries used a combination of secondary ingot together with approximately 35% in-house recycled A319 alloy and recycled foundry ingot to top-up for losses. Based on these charge make-ups and internal recycling rates, and assuming infinite recycling, the embodied energy for the metallic charge is 25 GJ/t for HPDC, 24 GJ/t for LPDC and 32 GJ/t for LPS; the differences being primarily due to the different recycling rates. These embodied energy values include the energy consumed for the production of the metallic silicon (122 GJ/t) [2] to alloy to 5% Si and for the production metallic copper (13.5 GJ/t) [2] to achieve 1.5% Cu in the as-cast product.

For the production of the aluminium cylinder blocks, the embodied energy in the centrifugally cast grey iron cylinder liners was also included. Based on the OEM survey results, the current study adopted an as-cast thickness of 7.5 mm (8.3 kg per set of four), with pre-machining prior to casting to 5.5 mm (6.1 kg/set), and finish machining to 1.5 mm (1.75 kg/set). No account was taken for bonding agents on the exterior wall of the liners to facilitate wetting with the aluminium parent material, or for the preheating of the liners. Assuming 95% of the liner material is recycled scrap, the embodied material energy for the cylinder liners is 12 GJ/t (188 MJ for a set of four liners).

The embodied energy associated with the sand used to cast the cylinder blocks depends on three factors: the mining, preparation, and transport of the sand; the amount of sand; and the type of binder used (green sand vs. resin-bonded core sand). For the resin-bonded sand, it was assumed that the cores used for aluminium and cast iron production were of the same composition. For aluminium, the average core weight in LPDC casting was 18 kg per cylinder block while the average weight of the complete core package used in LPS was 200 kg. For cast iron, the average core box package weighed 42.5 kg per cylinder block and the green sand demand was 181.3 kg per cylinder block. The corresponding energy per tonne of as-cast cylinder blocks ranged from 1 GJ for the LPDC cores (plus 1 GJ for the resin); 12 GJ for LPS core package (plus 14 GJ for the resin); and, for cast iron, 2 GJ for the core package, 2 GJ for the resin and 1 GJ for the green sand. The embodied energy content in the recycled sand was calculated to be 1.8 GJ/t for core sand and 0.2 GJ/t for green sand. No sand is used in high pressure die casting.

In all cases, the energy associated with the production of the metal dies for die casting, the core boxes for core shooting, and the pattern plates for cast iron green sand moulding was regarded as negligible and excluded from the analysis. The embodied material energy from all sources is summarised in Figure 2.

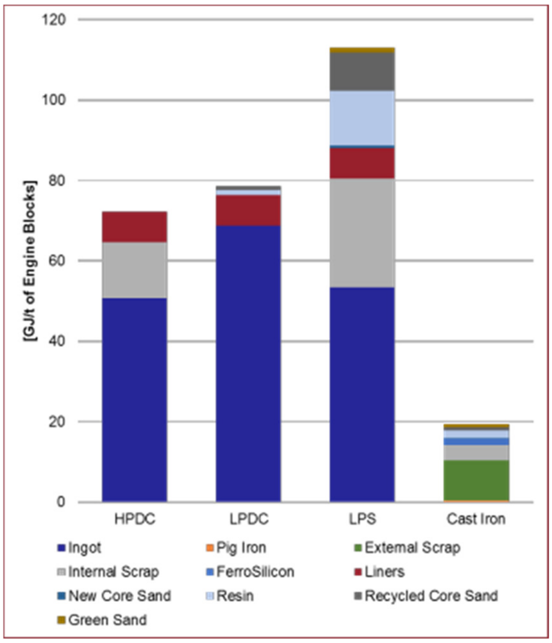


Figure 2: Breakdown of the embodied material energy (GJ) per tonne of cylinder blocks

Process Energy

In addition to the energy content embodied in the raw materials that arrive at the foundry, the life cycle analysis must also consider the energy consumed in each step of the process to produce the cylinder block. A range of energy values were obtained in the industry surveys and the literature data. Therefore, the data presented in this section represents the most representative values of the energy consumed in the various processing steps for HPDC, LPDC, LPS and cast iron cylinder block production.

- *Melting:* for aluminium, the melting energy depends on the type of furnace used, for example, gas tower, reverbatory, crucible or electrical induction. Allocating these furnace types to their respective facilities, the melting energies were 6.1 GJ/tonne of liquid metal for HPDC; 3.7 GJ/t for LPDC; and 9.8 GJ/t for LPS. For cast iron, all foundries used cupola melting. The melting energy varied from 3.6-4.0 GJ/t of liquid metal.
- *Holding:* the liquid metal is held in separate ‘holding’ furnaces to buffer the melting demand and, in aluminium, to allow for degassing and settlement of impurities. Holding consumed 2.5 GJ/t in HPDC and 1.5 GJ/t in LPDC. LPS had a considerably higher energy consumption of 6.5 GJ/t due to holding times of up to 13 hours to allow impurities to settle. Induction furnaces were used to hold cast iron, consuming 0.2 GJ/t.
- *Metal Loss:* for each process, a total metal loss of 2% during melting and metal transfer operations was assumed.
- *Casting Yield:* considering the gating, venting and feeding systems, the mould yield reported was 67% for HDPC, 65% for LPDC and 62% for LPS. Each of the grey iron foundries produced four cylinder blocks per mould, with no feeding, providing a yield of 76%.
- *Sand System:* core sand is not used in high pressure die casting. For LPDC, 18 kg of cold box cores were used for each cylinder block, corresponding to a manufacturing energy of 0.42 GJ/t of cylinder blocks and a sand reclamation energy of 0.54 GJ/t of engine blocks. For low pressure sand casting, the mould is entirely comprised of a cold box core package, weighing 200 kg per cylinder block. The process energy per tonne of cylinder blocks was 5.17 GJ for core manufacture; 0.96 GJ for mould assembly and 5.48 GJ for sand reclamation.

For cast iron, the cylinder blocks were produced in cold box core packages weighing 42.5 kg, contained in green sand moulds with 181.3 kg of green sand per casting. The process energy per tonne of cylinder blocks was 0.70 GJ for core manufacture; 0.61 GJ for green sand compaction and mould assembly, and 0.47 GJ for sand reclamation. For each process, 10% sand loss was assumed in sand reclamation.

- *Fettling:* the energy consumption for fettling was relatively small, approximately 0.5 GJ/t of finished cylinder block castings for both aluminium and cast iron.
- *Heat Treatment:* The heat treatment energy depends on the treatment cycle, the furnace efficiency and the number of castings per batch. The HPDC castings are typically stress relieved but not solution treated or aged, resulting in an energy of 2.1 GJ/t of raw castings (2.7 GJ/t of finished cylinder blocks). The LPDC and LPS castings were subjected to T6 or T7 heat treatment cycles, with energy consumption of approximately 6 GJ/t (7.7 GJ/t of finished cylinder blocks). Cast iron cylinder blocks do not require heat treatment.
- *Machining:* the process energy for machining was evaluated using the energy calculator developed by MAG IAS to determine power station requirements for the installation of a new machining facility. For aluminium, it was assumed that 18% of the cylinder block material and 78% of the cast-in liner is removed during machining. For cast iron, 20% is removed. The energy consumption was 2.1 GJ per tonne of machined aluminium cylinder blocks and 1.6 GJ/t of machined cast iron cylinder blocks. Considering the cylinder block weights in Table I, this corresponds to 10~15% less energy consumption to machine each aluminium cylinder block.
- *Impregnation:* aluminium impregnation strategies varied from 'leakers only' to 100% depending on the OEM. An average rate of 30% impregnation was adopted, corresponding to 0.1 GJ per tonne of finished cylinder blocks. Cast iron cylinder blocks are not impregnated.
- *Miscellaneous:* the categorisation of miscellaneous energy varied between the foundries surveyed. All foundries included services such as lighting, heating, ventilation and compressed air. Some foundries accounted for washing and painting or powder coating in miscellaneous while other foundries allocated these energies to other operations. As a result of the different classification, miscellaneous energy varied from 1.5 GJ per tonne of finished cylinder blocks for HPDC and cast iron, to 8.8 GJ for LPDC and 11.4 GJ for LPS.
- *Scrap:* the internal scrap rate for HPDC foundries was set at 8.5% to account for metallurgical scrap and die heat-up runs. The internal scrap rate for the LPDC and LPS foundries was 5% while the internal scrap rate for the grey cast iron foundries was 3%. The external scrap rate was set at 0.5% for all processes.

The process energy from each of the individual processing steps is compiled in Figure 3.

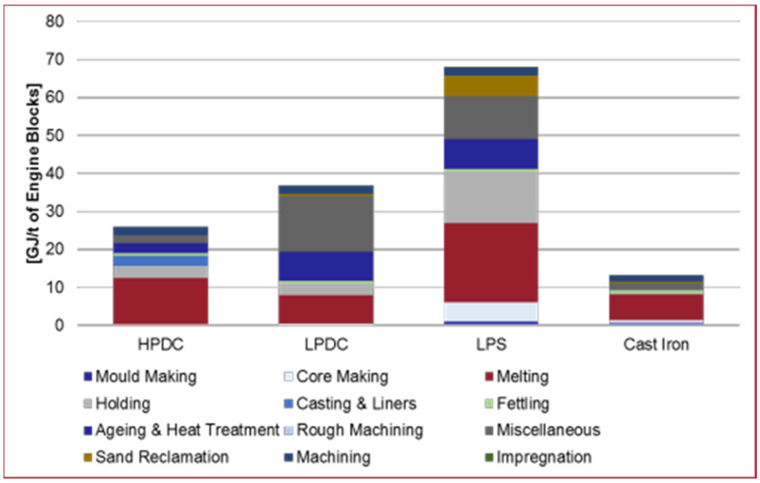


Figure 3: Breakdown of the embodied material energy (GJ) per tonne of cylinder blocks

Breakeven Driving Distance - Energy

The sum of the embodied energy from the raw materials and the process energy from the manufacturing steps provides the total Process Energy Burden (PEB) per tonne of cylinder blocks. The results of this research show that the process energy burden to produce one tonne of finished cylinder blocks is approximately 98 GJ for high pressure die casting, 116 GJ for low pressure die casting, 182 GJ for aluminium sand casting, and 32 GJ for cast iron. The aluminium sand casting has the highest PEB, primarily due to the high consumption of core sand and the long holding times used for degassing and settlement of impurities. Using the cylinder block weights provided in Table I, the total embodied energy in each cylinder block can be calculated, as shown in Figure 4. From the life cycle perspective, to provide a net benefit to society, the higher PEB accumulated during the manufacturing phase must be compensated for during the on-the-road use phase.

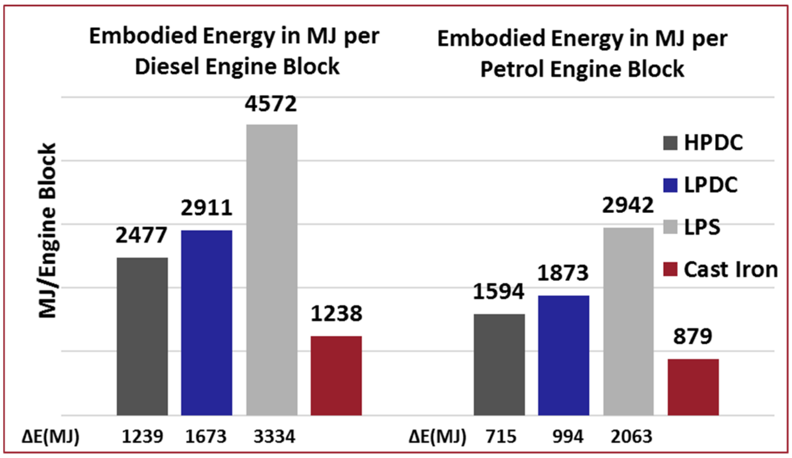


Figure 4: Embodied energy for diesel and petrol engine cylinder blocks, and the energy differentials relative to cast iron

The on-the-road breakeven driving distance (BED_e) required to compensate for the higher embodied energy is calculated as a function of the weight differential, the fuel savings provided by the weight reduction, and the energy content in either the diesel or petrol fuel. The base-case for fuel saving was 4.6% for each 5-10% of vehicle weight reduction [1]. For a modern 1.6 litre diesel engine, this corresponds to 0.15 litres of fuel saved for every 100 kg of weight saved and 100 km driven. For the petrol engine, the 4.6% base-case corresponds to 0.20 litres of fuel saved for every 100 kg of weight saved and 100 km driven. These values were linearly interpolated for the 9 kg weight reduction in the diesel vehicle (0.69% of the 1,300 kg vehicle) and the 7 kg weight reduction in the petrol vehicle (0.54%). From these data, and the process energy burdens shown in Figure 4, the energy breakeven distance can be calculated according to equation 1.

$$BED_e = \frac{\Delta PEB}{(\delta F_s \times E_f \times \Delta M\,)} \times 10000 \qquad \textit{Equation 1}$$

Where:

- ΔPEB is the process energy burden relative to cast iron (MJ/block; Figure 4)
- δF_s is the fuel saving in litres/100km/100kg (0.15 for diesel and 0.20 for petrol for the 4.6% base-case)
- E_f is the energy content in the fuel (38.6 MJ/litre for diesel and 34.2 MJ/litre for petrol)
- ΔM is the mass differential for the fully assembled engine (9kg for diesel and 7kg for petrol)

Correlations between weight reduction and fuel saving are generally based on savings of approximately 100 kg, where the primary weight reduction allows for low for secondary weight savings in the powertrain, gearing and other components. In the present case, where the weight saving approximately 10 kg, the direct weight reduction must contribute to fuel economy as part of a bundle, together with other weight reduction efforts. For the on-the-road breakeven calculation, a sensitivity analysis was conducted to reflect different levels of fuel saving. This included the 4.6% EPA base-case [1]; a lower value of 3% (0.10 litres of fuel saved for every 100 kg and 100 km for diesel and 0.15 litres of fuel saved for every 100 kg and 100 km for petrol) to reflect conclusions from the US National Research Council [3]; and a higher value of 6% (0.20 litres of fuel saved for every 100 kg and 100 km for diesel and 0.25 litres of fuel saved for every 100 kg and 100 km for petrol) as suggested by Casadei and Broda [4]. The actual weight reduction was applied linearly for each case. The results are presented in Table II for each of the three fuel saving scenarios and for each aluminium casting process.

Table II:
Energy breakeven distances (BED_e, in km) for aluminium cylinder blocks produced by HPDC, LPDC and LPS, assuming infinite recycling

Fuel Efficiency Savings*	**HPDC**		**LPDC**		**LPS**	
	Diesel	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**
3% [3]	481,000	330,000	621,000	434,000	1,081,000	778,000
4.6% [5]	240,000	150,000	322,000	210,000	645,000	435,000
6% [4]	180,000	120,000	240,000	166,000	480,000	345,000

**Note: published fuel saving values are for 5-10% weight reduction. Linear interpolation was applied for the actual 0.69% weight reduction for diesel and 0.54% weight reduction for petrol*

As discussed earlier, the initial bauxite refining and electrolysis processes are significant constituents of the aluminium process energy burden. The results presented in Table II assume the best-case scenario that the aluminium contained in every cylinder block has been infinitely recycled. With a global recycling rate of 85%, this assumption reduces the primary energy burden from approximately 98 GJ/t to approximately 30 GJ/t (primary energy content for pig iron: approximately 17 GJ/t). Because the assumption of infinite recycling reduces the breakeven distance, a further sensitivity analysis was conducted to show the impact of one, three, five, ten, and infinite recycling loops. The results of this sensitivity analysis are shown for the 4.6% fuel saving base-case in Figure 5. Figure 5 also indicates the average vehicle life based on published statistics from China, Germany, India, Japan, the US and the UK. According to these statistics, the average global vehicle life expectancy is 12.5 years. With a weighted-average annual driving distance of 17,000 km, this corresponds to a global average vehicle life of approximately 210,000 km. It is evident from Figure 5 that, for most scenarios, the substitution of cast iron with aluminium does not provide a net energy benefit to society.

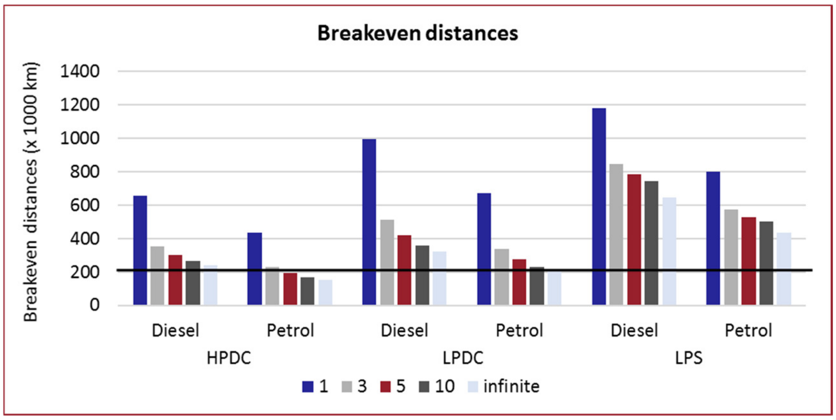


Figure 5: Effect of the number of recycling loops on the energy breakeven distance. The horizontal line represents the global average vehicle life of 210,000 km

Breakeven Driving Distance - CO_2

The CO_2 footprint for aluminium is influenced by the type of energy source used to produce the primary aluminium. For example, the generation of electricity from coal emits 355 tonnes of CO_2 for each GWhr while natural gas emits 181 tonnes of CO_2/GWhr. Hydro, wind and nuclear energy emit 9, 10 and 15 tonnes of CO_2/GWhr respectively [5].

The World Aluminium Organisation [6] publishes annual statistics on the breakdown of global aluminium production and the energy sources used to produce the electricity for refining and electrolysis. In 2015, China accounted for 54.7% of the global primary aluminium production, with the Gulf States being the second largest producer (8.8%) and North America third (7.7%). More than 90% of the primary aluminium production in China is produced using electricity derived from coal while 100% of the production in the Gulf States is based on electricity derived from natural gas. The North American split is approximately 75% hydro and 25% coal. Overall, 72% is based on fossil fuels (primarily coal and natural gas), while 28% of all primary aluminium production is based on renewable sources of energy (primarily hydro). These values were used, together with the raw materials mixes (primary aluminium and secondary aluminium with sweetener) previously allocated for HPDC, LPDC and LPS in the energy calculations to determine the embodied CO_2 burden at the start of the foundry process. Again, infinite recycling was assumed for the aluminium energy and CO_2 flows. For cast iron, all primary production was derived from coal-fired blast furnaces.

Within the foundry, an energy source was allocated for each step in the process, with some steps having two different energy sources assigned. For example, heat treatment has a proportion of energy from both natural gas and electricity while machining is entirely electrical. Where an electrical source of energy is used, the average world energy CO_2 footprint of 63 kg CO_2/GJ was adopted. For the other sources of energy, the CO_2 emission factors were based on data published by the Carbon Trust [7]. Ultimately, the conversion of the material energy and the process energy is presented as the CO_2 burden for HPDC, LPDC, LPS and cast iron in Figure 6.

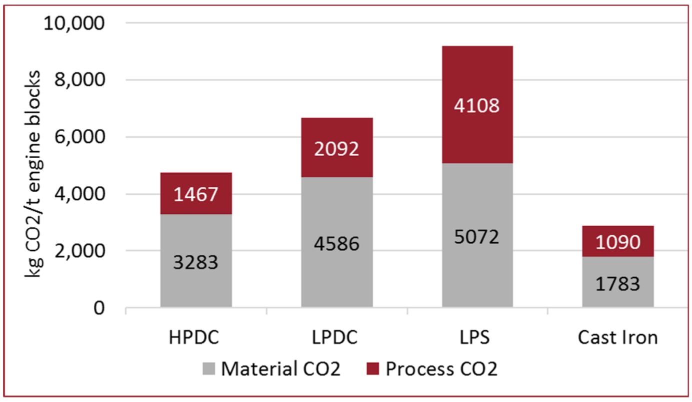


Figure 6: Summary of CO_2 burden per tonne of good castings for the different casting processes

Using the same methodology as was applied earlier to calculate the breakeven distance for energy, the breakeven distance needed to compensate for the higher CO_2 emissions associated with the production of an aluminium cylinder block can be determined according to Equation 2. The results, for the conditions of infinite recycling, are presented in Table III.

$$BED_c = \frac{\Delta C_b}{\delta F_s \times E_f \times C_f \times \Delta M} \times 10000 \qquad \textit{Equation 2}$$

Where:

- ΔC_b is the CO_2 burden relative to cast iron (kg CO_2/block; Figure 6)
- δF_s is the fuel saving in litres/100km/100kg (0.15 for diesel and 0.20 for petrol for the 4.6% base-case)
- E_f is the energy content in the fuel (38.6 MJ/litre for diesel and 34.2 MJ/litre for petrol)
- C_f is the carbon emission factor for diesel (0.0694 kg CO_2/MJ) and for petrol (0.0667 kg CO_2/MJ)
- ΔM is the mass differential for the fully assembled engine (9kg for diesel and 7kg for petrol)

Table III:
Breakeven distances for CO_2 (BED_C, in km) for aluminium cylinder blocks produced by HPDC, LPDC and LPS, assuming infinite recycling

Fuel Efficiency Savings*	**HPDC**		**LPDC**		**LPS**	
	Diesel	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**
3% [3]	210,000	163,000	426,000	330,000	706,000	547,000
4.6% [5]	140,000	106,000	284,000	215,000	471,000	356,000
6% [4]	111,000	81,000	426,000	165,000	371,000	274,000

**Note: published fuel saving values are for 5-10% weight reduction. Linear interpolation was applied for the actual 0.69% weight reduction for diesel and the 0.54% weight reduction for petrol*

Conclusions

A detailed analysis of every step of the manufacturing process, from mining through to on-the-road use, has shown that the substitution of a cast iron cylinder block by an aluminium cylinder block does not provide a net benefit when comparing the total manufacturing energy to the fuel savings realised due to weight reduction.

The breakeven distance varies significantly depending on the foundry casting technology used to produce the aluminium cylinder block, but is in most cases well beyond the average global vehicle life of 210,000 km. For aluminium, the lowest manufacturing energy is achieved with high pressure die casting, where there is no energy consumption for the manufacturing, handling and recycling of sand, and where the liquid metal holding times are short. The highest manufacturing energy was incurred in low pressure sand casting where the core package weighed 200 kg per cylinder block and metal holding times were up to 13 hours to allow for degassing and settlement of impurities. This conclusion has important implications for V-type cylinder blocks which, when produced in aluminium, predominantly use sand casting to accommodate the complex architecture and internal coring requirements.

The breakeven driving distance, based on fuel savings of 4.6% for each 5-10% of weight saved as adopted for the US 2017 midterm CAFE review, and assuming the favourable conditions of infinite recycling, give breakeven distances for energy (BED_e) of between 185,000 km (HPDC petrol) and 560,000 km (LPS diesel). This corresponds to CO_2 breakeven distances (BED_c) of between 106,000 km and 471,000 km. A sensitivity analysis of the number of recycling loops has shown that, if the actual recycling rate is five to ten loops rather than infinite, the breakeven distances increase by approximately 10-30% for both die casting processes, and by approximately 5-10% for sand casting.

The present study, based on a comprehensive survey of the iron and aluminium supply industries, engine design consultancy firms and OEMs, clearly demonstrates that current tailpipe legislation can lead OEMs to select materials that actually increase cradle to grave energy consumption and CO_2 emissions. For most of the manufacturing scenarios investigated in this study, the breakeven distance for aluminium cylinder blocks is well beyond the vehicle life.

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