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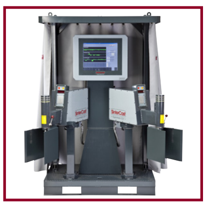
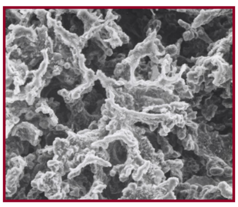
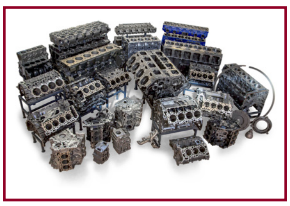
Cast Iron: We just need to get better at telling our story

Cast Iron: We just need to get better at telling our story

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Introduction

Emissions legislation in the automotive industry focusses entirely on tailpipe emissions, with no consideration for the CO_2 generated during the production of the vehicle or during the production, delivery and consumption of the fuel. To ensure that legislators make the best decisions for society, the full life cycle emissions must be considered. For the cast iron foundry industry, the current focus on tailpipe emissions presents two significant challenges. First, in the quest for weight reduction and fuel economy, many OEMs have replaced cast iron components with aluminum. However, the production of aluminum consumes significantly more energy than cast iron – both during primary manufacturing and in the foundry. Second, while battery electric vehicles may not generate tailpipe emissions, the production of the batteries and the production of the electricity does generate CO_2. The only difference is the location at which the emissions are released. Are the trends toward aluminum and electrification really better for society? Will the current legislation really make the world a better place? Maybe the cast iron foundry industry just needs to get better at telling its story.

Life Cycle Analysis – Cast Iron vs Aluminum

To determine if the use of aluminum provides a net benefit to the environment, 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 gasoline engines [1]. The study included interviews with more than one hundred industry experts from OEMs, engine design consultancy firms, cast iron and aluminum foundries, heat treatment facilities, raw material and recycling suppliers, and machining companies across the western world.

The Cranfield research focussed on the base-case of a 1.6 litre four-cylinder engine with a deep-skirt cylinder block. For the aluminum cylinder block, three different 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 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.

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

Diesel			**Gasoline**		
Aluminum*	Cast Iron	Difference	Aluminum*	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 aluminum 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 (0.54%) for the gasoline engine and 9 kg (0.69%) for the diesel engine. 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, as defined in the 2017 EPA midterm fuel economy review in the United States [2].

The total life cycle energy for producing a cast component is equal to the sum of the *embodied energy* in the raw materials that arrive at the foundry, plus the *process energy* consumed in each of the individual manufacturing steps (foundry, machining and heat treatment) needed to convert the raw materials to a finished component.

The embodied energy begins with the energy required to mine, process and convert the mineral ores to primary metal. Figure 1 shows that the production of one tonne of pig iron from a blast furnace requires approximately 17 GJ (125 GJ/m^3). The energy required to produce one tonne of primary aluminum 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 aluminum recycling. To provide the best-case scenario for both materials, infinite recycling was assumed to amortise the initial embodied energy content.

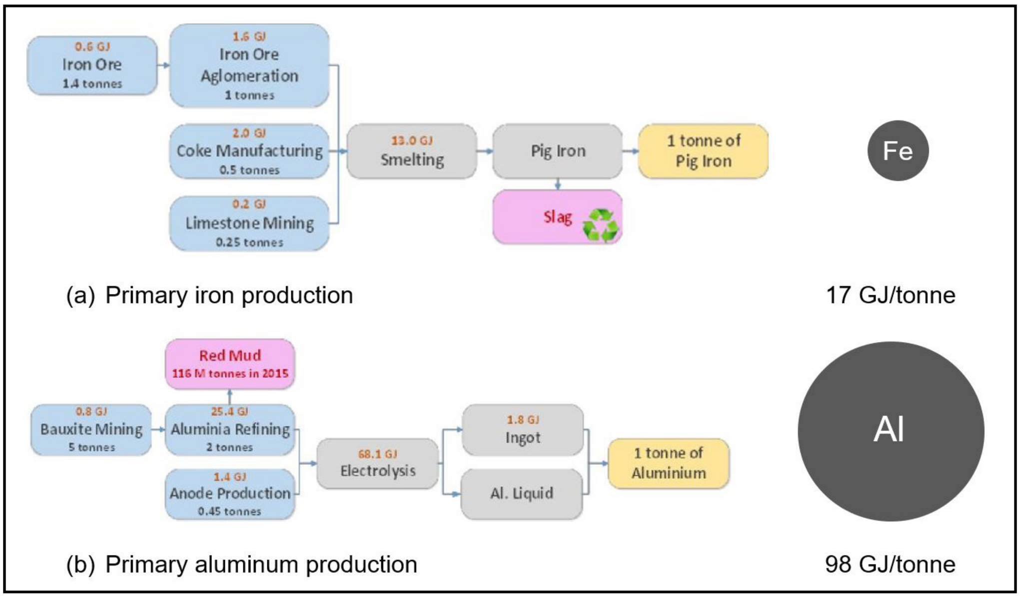

Figure 1: Process steps and associated energy to produce one tonne of primary metal

It is estimated that the iron foundries evaluated in the Cranfield study account for more than 75% of the cast iron cylinder blocks produced in Europe and the Americas. These foundries all used cupola melting, with an average charge make-up of 91% recycled material and 9% pig iron. 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 energy content of all alloying elements greater than 1% was also included in the analysis. For cast iron, this included 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 aluminum foundries evaluated in the Cranfield study represent more than 50% of the aluminum cylinder block production in Europe and the Americas. The aluminum 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) [3] to alloy to 5% Si and for the production metallic copper (13.5 GJ/t) [3] to achieve 1.5% Cu in the as-cast product.

For the production of the aluminum cylinder blocks, the embodied energy in the centrifugally cast grey iron cylinder liners was also included. Based on the OEM survey results, the Cranfield study adopted an as-cast thickness of 7.5 mm (8.3 kg per set of four), machined 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 aluminum 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 aluminum and cast iron production were of the same composition. For aluminum, 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. The high pressure die casting of aluminum does not use any sand.

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.

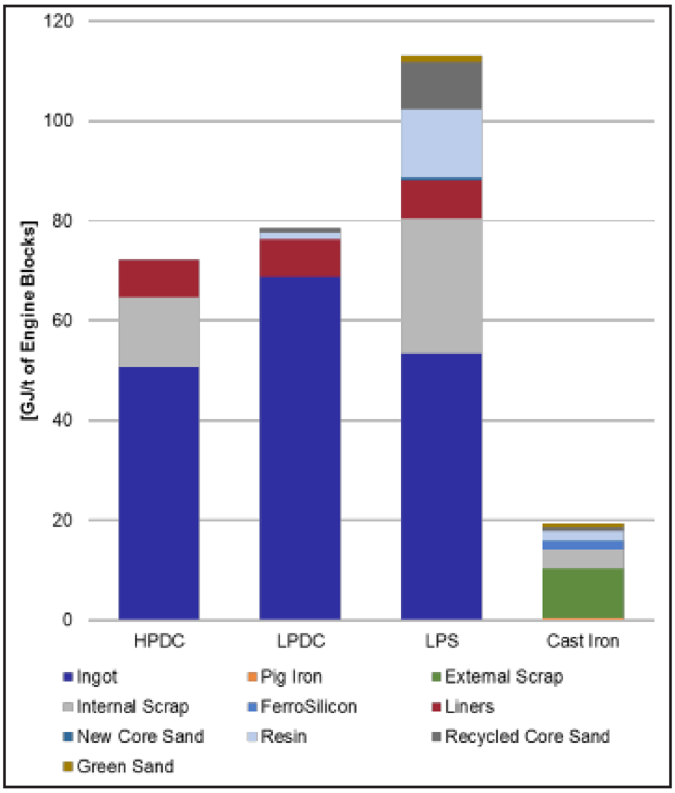

Figure 2: Breakdown of the embodied material energy (GJ) per tonne of cylinder blocks

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 for cast iron cylinder block production.

- *Melting:* for aluminum, 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 to buffer the melting demand and, in aluminum, 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 coremaking; 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 coremaking; 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 aluminum and cast iron.
- *Heat Treatment:* The heat treatment energy depends on the treatment cycle, hot-charge or cold-charge, 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 aluminum, 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 aluminum 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 aluminum cylinder block.
- *Impregnation:* aluminum impregnation strategies varied from 'leakers only' to 100% preventive, 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.

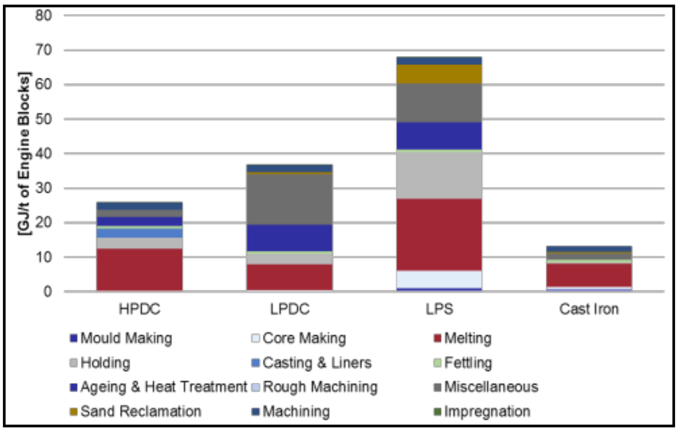

Figure 3: Breakdown of the embodied material energy (GJ) per tonne of cylinder blocks

Breakeven Driving Distance

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 the Cranfield study showed 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 aluminum sand casting, and 32 GJ for cast iron. The aluminum sand casting has the highest PEB 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 is 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.

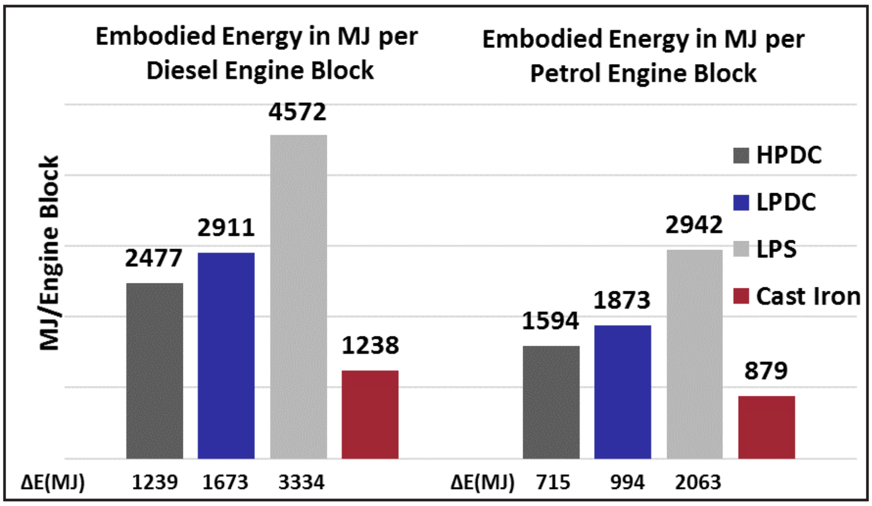

Figure 4: Embodied energy for diesel and gasoline engine cylinder blocks, and the energy differentials relative to cast iron

The on-the-road breakeven driving distance for energy (BED_e) required to compensate for the higher embodied energy is calculated as a function of the weight difference, the fuel savings provided by the weight reduction, and the energy content in either the diesel or gasoline fuel. 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 gasoline 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 gasoline 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 the cast iron (MJ/block; Figure 4)
- δFs is the fuel saving in litres/100km/100kg (0.15 for diesel and 0.20 for gasoline for the 4.6% base-case)
- Ef is the energy content in the fuel (38.6 MJ/litre for diesel and 34.2 MJ/litre for gasoline)
- ΔM is the mass differential for the fully assembled engine (9kg for diesel and 7kg for gasoline)

Using the fuel saving of 4.6% for every 5-10% of vehicle weight reduction, as defined in the 2017 EPA midterm fuel economy review in the United States [2], the breakeven distance for the gasoline engine was determined to be 150,000 km for the HPDC aluminum block; 210,000 for the LPDC block; and, 435,000 km for the sand cast aluminum block. For the diesel engine, the breakeven was significantly longer due higher diesel fuel efficiency, ranging from 240,000 km for HPDC; 322,000 km for LPDC; and, 645,000 km for sand casting. With an average vehicle life in China, Germany, India, Japan, the US and the UK of 210,000 km, these breakeven distances show that the use of aluminum does not always provide a net benefit to society.

It must also be noted that the breakeven distances stated above are based on the assumption of infinite recycling, providing the best-case scenario for aluminum. 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). Figure 5 summarizes the results of a sensitivity analysis, showing the impact of one, three, five, ten, and infinite recycling loops, based on the 4.6% fuel saving. The horizontal line in Figure 5 indicates the average vehicle life of approximately 210,000 km. It is evident from Figure 5 that, for most scenarios, the use of aluminum instead of cast iron does not provide a net energy payback within the life of the vehicle.

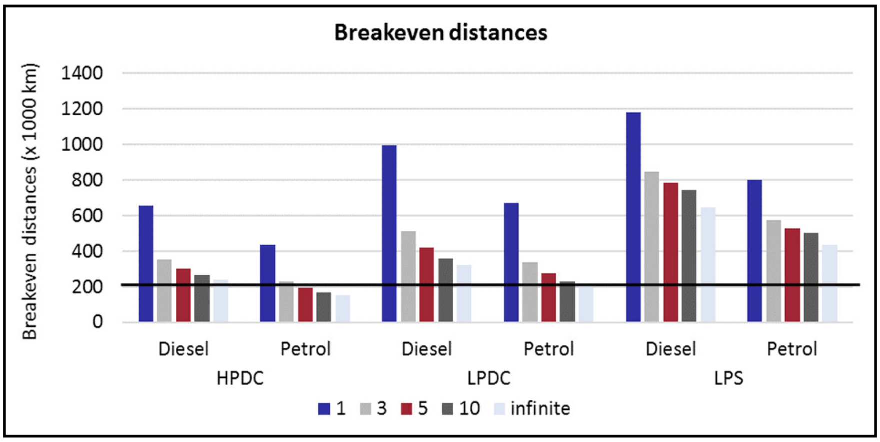

Figure 5: Effect of the number of recycling loops on the energy breakeven distance. The horizontal line represents the global average vehicle life of 210,000 km

Life Cycle Analysis – Internal Combustion vs Electrification

It has recently become common to refer to battery electric vehicles as "zero emissions vehicles". However, this refers only to the tailpipe emissions and excludes the CO_2 emitted during the manufacture of the vehicle; the provision of the fuel (or electricity); and, the end-of-life recycling. Accordingly, promoting battery electric vehicles as zero emissions vehicles risks misleading consumers and legislators alike.

The full environmental impact of electric vehicles must include the additional energy needed to manufacture the batteries and the emissions associated with the generation and provision of the electricity used to charge the batteries. In a full life cycle analysis, the material and energy needed to install the charging infrastructure should also be included. For a typical mid-size vehicle, battery production adds 15% to the CO_2 footprint associated with vehicle manufacture and assembly. For a full-size vehicle, the larger battery pack adds 60-70% to the manufacturing CO_2 emissions. This naturally means that small cars are better suited to electric powertrains, while for SUVs and pick-ups, bigger batteries mean more precious metals, more electricity in manufacturing, more weight in the vehicle, more cost, and a more difficult CO_2 payback. Recent well-to-wheels studies [4-6] indicate that the total life cycle CO_2 of internal combustion and electric vehicles is not significantly different, and that electric vehicles can have higher life cycle CO_2 emissions.

Figure 6 shows a typical life cycle analysis for passenger vehicles with gasoline, diesel, hybrid, battery and fuel cell powertrains. The total CO_2 emitted over the 200,000 km vehicle life is comprised of the emissions incurred during the production of the vehicle, the end of life recycling, the provision of the liquid fuel or the electricity, and the emissions during the on-the-road use phase. While it is obvious that the gasoline vehicle has the highest CO_2 tailpipe emissions, it is equally obvious that the battery electric vehicle has the highest manufacturing emissions. Over the entire life cycle, the CO_2 emissions of the diesel vehicle (135 g/km) are only 4.2 tonnes higher the battery electric vehicle (114 g/km). In Europe, carbon trading schemes for manufacturing facilities are based on buying and selling CO_2 credits at EUR 7.00 (approximately USD 8) per tonne. Applying this legislated value of CO_2 emissions to passenger vehicles, the value of the reduced CO_2 emissions over the lifetime of the battery electric vehicle is approximately USD 35. But, the US federal and state governments provide subsidies of approximately USD 10,000 for each battery electric vehicle. Surely the money would be better spent removing old vehicles from the public roadways.

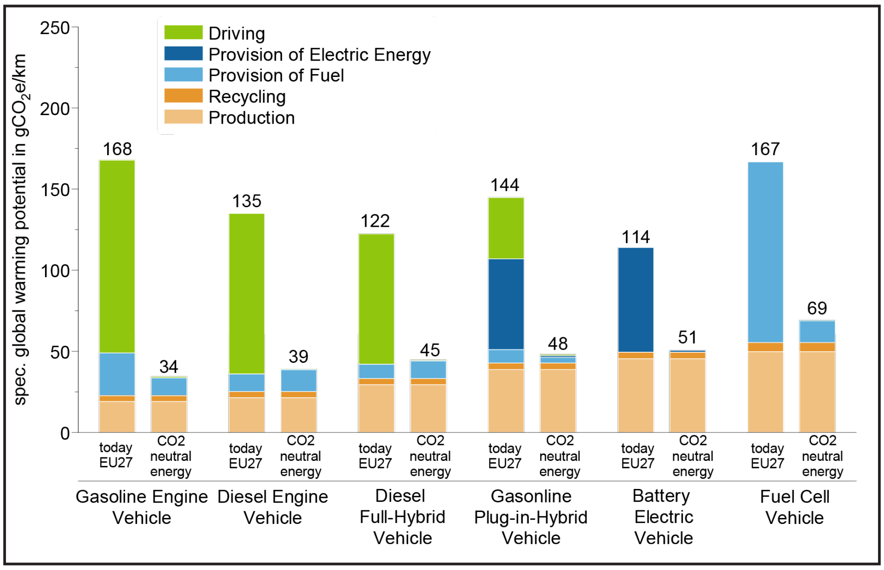

Figure 6: Life cycle analysis conducted by IAV GmbH, Germany, based on a 200,000 km vehicle lifespan [4]

Figure 6 also indicates the potential future life cycle emissions if the energy supply was CO_2 neutral, for example, electricity from windmills and solar panels; or, liquid fuels from biomass or carbon capture. In this scenario, it is clear that the best solution for society is the internal combustion engine, with carbon-neutral liquid fuels. A similar life cycle study was conducted by FEV in Germany in 2017 (Figure 7). However, the FEV study included the replacement of the battery pack during the life of the battery electric vehicle. Based on the 2015 electricity grid in Europe, the battery electric vehicle (BEV) has higher life cycle CO_2 emissions than either the gasoline engine (SI – spark ignition) or the diesel engine (CI – compression ignition). There is no net benefit to society. Similar the IAV study shown in Figure 6, the FEV study indicates that, with the future availability of carbon-neutral fuels, gasoline and diesel engines will have lower life cycle CO_2 emissions that either battery electric vehicles or fuel cell vehicles.

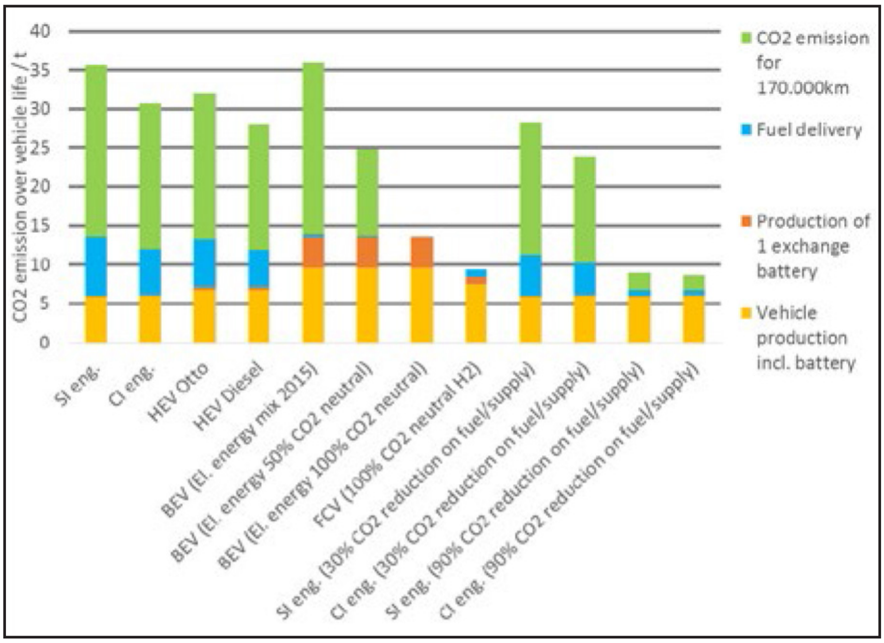

Figure 7: Life cycle analysis conducted by FEV GmbH, Germany, based on a 170,000 km vehicle lifespan [5]

The majority of the electric power supply in the main car-buying regions of continental Europe, China, India and the United States is derived from fossil fuels. The conversion of these fuels to electricity emits CO_2, NO_x, particulates and toxins, including lead and mercury. Therefore, the impact of the electrical energy source on the environmental friendliness of battery vehicles must also consider the effect of these emissions on mortality rates, as evaluated by the University of Minnesota [7]. As illustrated in Figure 8, the study estimated that, if 10% of the vehicle miles travelled in the US in 2020 were driven by diesel cars, 870 deaths would be incurred due to air quality. However, if 10% of the vehicle miles travelled in the US in 2020 were driven by battery electric vehicles, powered by the 2020 national grid, 1,610 deaths would be incurred due to air quality. This stark result exemplifies the need for legislators to adopt a holistic approach that considers life cycle emissions, and to establish legislation that leads provides the best overall solution for society.

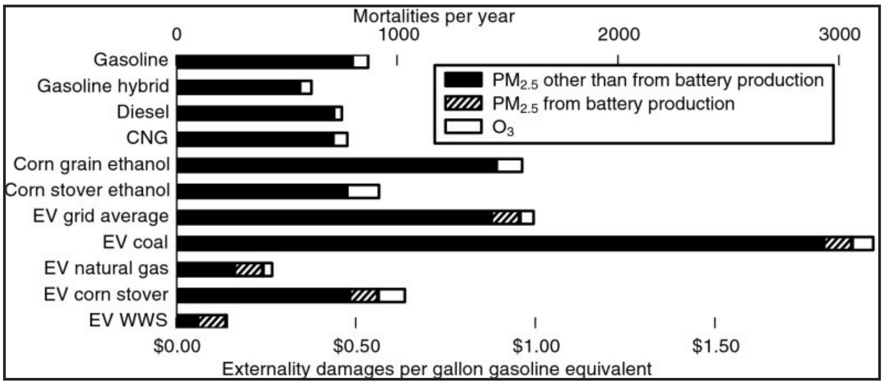

Figure 8: The generation of electricity from fossil fuels emits CO_2, NO_x, particulates and toxins. Life cycle studies show that a conversion to electric vehicles will not necessarily result in an improvement of public health [7]

Conclusion

The American journalist H. L. Mencken famously said that, “for every complex problem, there is a solution that is clear, simple, and wrong”. On the surface, it seems obvious that the substitution of cast iron components with aluminum reduces weight, improves fuel economy and reduces CO_2 emissions. Equally, it seems obvious that the substitution of internal combustion engines with battery electric vehicles reduces CO_2 emissions, curbing climate change. However, life cycle analyses show that these perceptions are oversimplified; the use of aluminum components and electric vehicles doesn’t always provide a net benefit to society.

The production of primary aluminum consumes approximately five times more energy than the production of pig iron. Even when this up-front energy penalty is amortised under the assumption of infinite recycling, it is difficult for the weight saved by the use of aluminum to achieve an energy breakeven within the vehicle lifetime. Small components produced by high pressure die casting, with no sand cores and short liquid metal holding times, may provide a CO_2 breakeven, but for large sand castings such as cylinder blocks, the payback can often be more than double the vehicle life. Similarly, up-front battery production and end-of-life battery recycling constitute a large handicap on the total energy consumption associated with electric vehicles.

The current focus on tailpipe emissions often compels engineers – and OEMs – to make decisions that satisfy legislation, but simultaneously result in energy, CO_2, and health penalties to society. The cast iron foundry industry can play an active role in guiding legislators and educating consumers on the need to consider the entire life cycle. Our industry has an excellent track record of promoting the strength and cost advantages of cast iron, now it is time to add life cycle energy and CO_2 benefits to the cast iron quiver.

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