Driving better material choices for automobiles

The impact of low CO_2 footprint aluminium on life cycle emissions

White Paper

March 2018

RUSAL

Executive Summary

Designing an Al-Intensive vehicle with half the BIW and all closures made of Al reduces weight and overall life cycle emissions by **12.6%** for internal combustion engine vehicles (ICEVs), compared to a baseline steel ICEV, C-segment. The carbon payback occurs at **63,300 km** due to the initial increase in material emissions, and further use-phase fuel economy improvements. Choosing low CO_2 Al in the Al-Int vehicle further reduces life cycle emissions by **17%** compared to the baseline steel ICEV (C-segment), with a carbon payback occurring at just **8,400 km**, an improvement of **54,900 km**.

The reduction in carbon emissions of switching to low CO_2 Al-Intensive BIW and closures for battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are different than ICEVs due to increased material and manufacturing emissions impacts of the powertrains. Further, the carbon intensity of the electricity source is a particularly important topic with the electrification of vehicle fleets. Simply switching to low CO_2 Al for an already Al-Int BEV reduces its life cycle emissions by **6.2%**, with ICEVs (**4.7%**) and PHEVs (**5.5%**).

Lightweighting passenger vehicles with low CO_2 Al is a Gigaton solution for global CO_2 emissions on all powertrains studied.

The goal of this study is to determine the most effective material substitute in lightweighting (LW) for steel in passenger vehicles by defining the differentiated life cycle CO_2 emissions impacts of BIW and closure materials in BEVs, PHEVs, and ICEVs for various vehicle segments - A, C, and E. Further, this study takes a life cycle analysis (LCA) perspective to determine the value low CO_2 Al brings in terms of a carbon payback to meet OEMs' product life cycle CO_2 footprint goals. The reductions in global CO_2 emissions from choosing low CO_2 Al in passenger vehicles are significant - **it will take 4 years of current light duty production levels to achieve a Gigaton (billion) CO_2 impact**.

Not all aluminium is created equal. Global Al production carbon intensities range from 2 – 41 T CO_2 / T Al per smelter (full scope).

A literature review of 24 LCAs from industry and academic sources have concluded that the most effective way to reduce vehicle weight to meet national fuel economy targets is to reduce weight by designing Al-Intensive vehicles, as aluminium material substitution (AMS) demonstrates the most attractive carbon payback over the life cycle of the vehicle. **Low CO_2 Al achieves a much quicker carbon payback to reduce the overall vehicle life cycle footprint.**

LW has tangential impacts to the overall life cycle emissions of the vehicle. Regulators, engineers, and automotive executives must consider the carbon footprint of the substitutive LW materials in order to determine if their choice is truly improving the emissions performance of passenger vehicles throughout their lifetime. With this study, OEMs and regulators have the knowledge to holistically address the carbon emissions in the use-phase of their vehicles along with their supply chain, in order to truly address emissions for the life cycle of their vehicles.

Contents

List of Abbreviations

Al	Aluminium
AHSS	Advanced High Strength Steel
AMS	Aluminium Material Substitution
BEV	Battery Electric Vehicle
BIW	Body-in-white
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
eq	Equivalent
EPD	Environmental Product Declaration
EOL	End-of-life
GHG	Greenhouse Gas
GWP	Global Warming Potential
ICEV	Internal Combustion Engine Vehicle
kg	Kilogram
LCA	Life Cycle Analysis
Low CO_2 Al	Low Carbon Aluminium
LW	Lightweighting
MWh	Megawatt hour
NEDC	New European Driving Cycle
PHEV	Plug-in Hybrid Electric Vehicle
T	Tonnes (metric)
TTW	Tank-to-wheel
UHSS	Ultra High Strength Steel
WTW	Well-to-wheel

1. Study Scope

1.1 Lightweighting and Material Substitution

The passenger automobile market is changing faster than ever with digital innovation, vehicle electrification, and improved design. Automobile manufacturers are facing increased pressure by corporate average fuel economy (CAFE) targets (measured in km / liter) and greenhouse gas (GHG) standards (g CO_2eq / km) to reduce the mass of their vehicles, develop more efficient technologies, and incorporate alternative vehicles in their fleets. Many of these ambitious goals by 2025 are below 100 g CO_2eq / km.

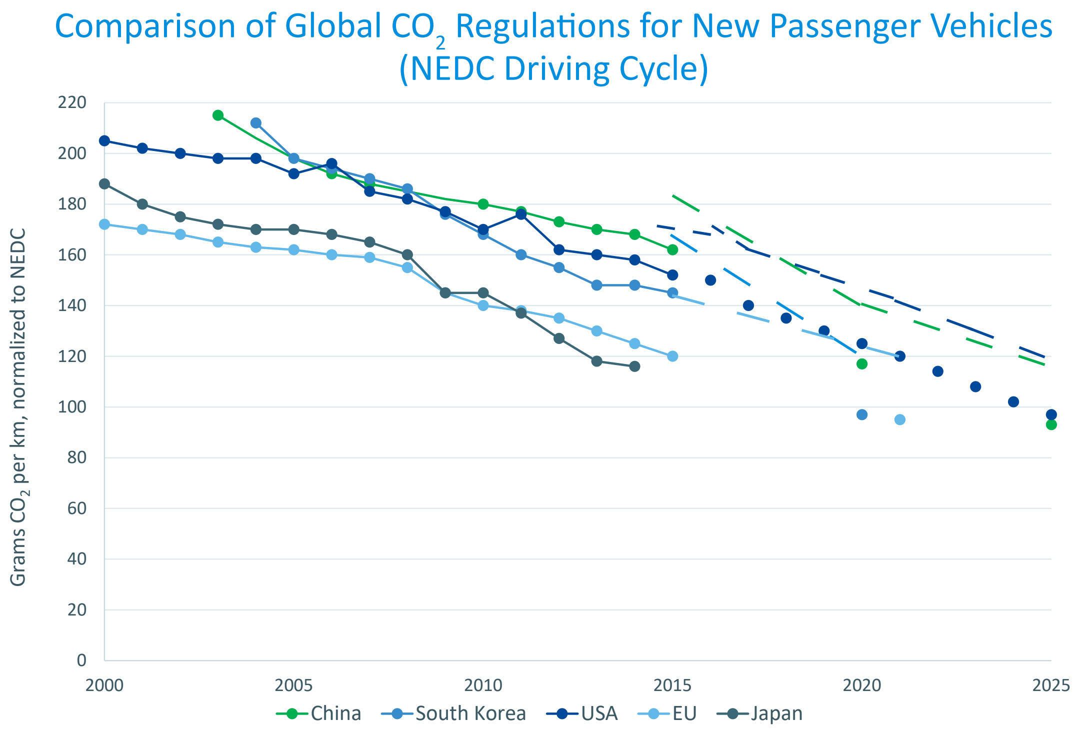

Figure 1 adapted from (ICCT 2016)

The most cost effective way to meet these environmental and efficiency goals is to reduce vehicle weight, primarily through substituting a 'baseline' steel body-in-white (BIW), with lighter materials, without compromising safety or quality. The BIW is one of the primary contributors to the vehicle's weight, approximately 25% for passenger vehicles. Aluminium, advanced high-strength steel (AHSS), magnesium, and carbon fiber are currently on top of the list to reduce BIW weight (Ducker Worldwide 2016).

This is particularly important for BEVs due to the weight of additional battery capacity as a typical BEV weighs more than an ICEV of the same segment (Hottle 2017). For example, segment B vehicles on similar platforms such as the Chevrolet Sonic Hatchback (ICEV) and the Chevrolet Bolt (BEV) show a 300 kg difference after the addition of battery and motors, along with the subtraction of the engine and transmission.

Lighter vehicles require less powertrain demand, and thus operate with lower use-phase emissions. This 'use-phase', defined as the emissions from powering the vehicle over its usable life, attributes the majority of emissions of the life cycle – almost 80% for a typical ICEV, and can be varied for PHEVs and BEVs due to the carbon intensity of the electricity mix (Kim and

Wallington 2013) (Seifert 2017). An important distinction is between the tank-to-wheel (TTW) and well-to-wheel (WTW) basis – for TTW, BEVs are immensely cleaner on a GWP basis due to the lack of tailpipe emissions, but their WTW emissions directly depend on the carbon footprint of their electricity source. The rest of the life cycle contributions are broken down into materials production, vehicle manufacturing, and end-of-life processing.

Previous studies have determined that LW initiatives typically necessitate the use of materials which have a higher carbon footprint than the historically baseline BIW metal, steel, due to higher production energy demands. The use of the alternative materials from substitution indicates there is a need to think holistically in order to not 'shift' the environmental burden to other sectors. As fuel efficiency regulations are implemented by 2025, most vehicles will see a significant reduction in the use-phase life cycle emissions and smaller increases in material production and manufacturing.

This is referred to as the *'Gigaton solution'* - a drastic reduction of carbon emissions from the use of LW materials (Modaresi 2014).

Practical experience shows that for BIW components, 1 kg of Al replaces between 1.66 and 1.87 kg of steel, while in chassis could be 1 kg to 2 kg replacement (Stodolsky 1995). For a 10% mass reduction with powertrain resizing, the fuel consumption reductions for ICEVs & PHEVs were 7% and 6.3%, respectively (Kim and Wallington 2016). This incorporates direct and indirect downsizing, defined further in the study. A range of 19-31% weight reduction for an ICEV (270 to 460 kg) is possible with intensive use of aluminium, resulting in a fuel economy savings of 12-20% over steel (Cheah 2010). These ranges will be further refined by powertrain and car segment based on the literature review and developed model.

1.2 Life Cycle Assessment

Many design constraints and trade-offs such as cost, functionality, safety, and durability determine the material of choice (Hottle 2017). Automotive designers must be cognizant of these trade-offs to determine the amount of material which can be substituted per part, as the life cycle impacts for the entire vehicle will change if just one part is materially substituted.

Life cycle carbon accounting is a necessary method to prove the value of the low carbon footprint substitution material to automotive industry customers (such as metals transformers and semi-fabricators) and end-users (OEMs) with the ongoing innovation around LW. Although each automotive part is chosen from a select group of qualified suppliers, it is important that OEMs and regulators ''move beyond single product LCAs and consider the entire vehicle fleet, its development over time, and connection to the material industries'' (Modaresi 2014). Though many OEMs do not publicly disclose their incorporation of raw materials' carbon footprint as a design aspect, there are initiatives by many to evaluate the emissions of their supply chains (Scope 3 emissions) to input into internal LCAs.

One goal of this study is to determine the most effective material substitute for steel by defining, through differentiated life cycle CO_2eq emissions impacts of material production in ICEVs, BEVs, and PHEVs for various vehicle segments. Further, the study determines the impact of using low CO_2 Al in the Al-Intensive vehicles through a part-by-part vehicle material component model, as not all Al is created with similar carbon footprints. For this study, an Al-Intensive vehicle is defined as having all closures and half the BIW made of Al, a composition that is much alike that of the Audi A8 2017. We use LCA methodology with the components:

(1) material extraction / pre-manufacturing (2) manufacturing, (3) use, and (4) end of life (EOL), in order to assess the full carbon dioxide equivalent (CO_2eq) implications of AMS.

This is part of RUSAL's research into the benefits of using low CO_2 Al for the automotive sector. For this study, low CO_2 Al is defined as having a verified carbon footprint of < 4 T CO_2 / T Al, over three times better than the world average (13.4 T CO_2 / T Al), both smelter Scope 1 & 2 (IAI 2017). Primary aluminium producers commonly communicate CO_2 emissions in smelter Scope 1 & 2. As LCAs require full scope figures, this study used IAI averages for bauxite and alumina production CO_2 emissions in order to develop full scope primary aluminium CO_2 emissions. This added 2.4 T CO_2 / T Al from bauxite and alumina production to define low CO_2 Al as 6.4 T CO_2 / T Al, full scope. Explanation on the use of low CO_2 Al in the LCA model is defined further. The global primary steel and AHSS production carbon intensity average is 2.4 T CO_2 / T steel, full scope, with far less deviation from the average compared to Al (Lewis 2014) (Quader 2015).

A literature review of 24 LCAs from industry and academic sources was performed to gather a diverse set of opinions in a field typified with a variety of assumptions, methodologies, and data sources. In the literature, studies focusing on LW/AMS of ICEVs are much more common than those focused on PHEVs and BEVs. Even with commonly used standardization systems such as ISO-14040 and ISO-14044, it was necessary to discern relevant information for BIW weight reduction, lifetime driving distance, and emissions contributions for a level comparison.

The traceability and assurance of carbon footprint verification statements for low CO_2 Al smelters will unlock the potential for the Al entire value chain to be more knowledgeable about its life cycle carbon footprint. This will initiate vehicle sustainability communications such as environmental product declarations (EPDs) and product LCAs with the help of verified trustworthy data sources. A significant number of OEMs currently conduct LCAs for their vehicles, but not all are publicly available. LCAs from Audi and Toyota were reviewed due to the high data transparency in their studies compared to competitors.

As discussed in (Liu and Muller 2012),

> *''there is a growing need to critique the state and utility of low carbon aluminium applications in specific product systems to better inform industry and government policy-making. Low carbon aluminium is increasingly used to demonstrate the GHG emissions 'payback' or 'avoidance' resulting from its downstream applications.''*

Although current marketing factors point out that LCAs and 'green' production methods have little impact on consumer preferences, as they are not willing to pay a visible premium for a 'clean' or recyclable car, there is a movement to certify low-carbon supply chains (Chanaron 2007). For example, BMW's i3 is characterized by this marketing strategy: lowering the manufacturing footprint through powering their Leipzig production plant with 100% renewable energy, along with sourcing raw materials made exclusively with renewables (BMW). Acknowledging the impacts of LW with AMS, it is clear that lowering automotive life cycle emissions must be done from all aspects of LCAs to benefit both the product and OEM efforts towards sustainability.

1.3 Vehicle Weight Reduction and Market Dynamics

A 'rule of thumb' is that a 10% weight reduction results in a lifetime fuel consumption reduction of 3-7% without regenerative braking, and 1-5% with – but this tells only part of the vehicle life cycle emissions story (Kim and Wallington 2016). All OEMs are driven by fuel efficiency

Approximate Passenger Vehicle Mass Breakdown by System

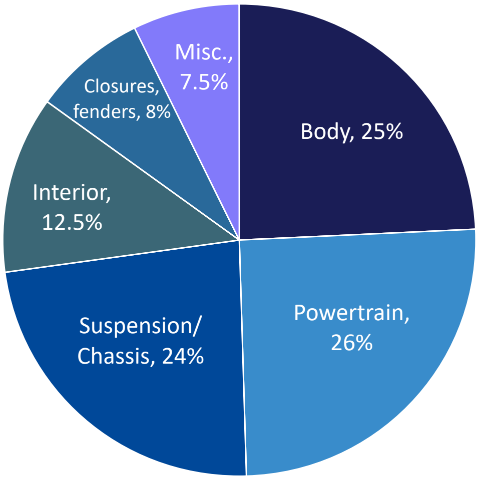

Figure 2 from (Mayyas 2012)

regulations to LW their cars, but they are not regulated for the manufacturing or raw material fabrication emissions. This is intuitive as the majority (~80%) of ICEV's life cycle emissions come from the use-phase of the vehicle (Kim and Wallington 2013) (Seifert 2017).

Achieving significant LW requires not only material substitution (direct LW), but also downsizing of other vehicle components in addition to the vehicle structure, referred to as indirect LW. Direct mass reduction makes it possible to reduce vehicle weight by downsizing other components (ex. BIW, powertrain, closures, fuel tank), given the inherently higher efficiency of lighter vehicles.

This subsequent weight reduction is defined as indirect mass reduction. Several literature sources claim a 2:1 ratio for the direct to the indirect weight saving (Kim H.J. 2010).

An approximate passenger vehicle mass breakdown by system is provided in Figure 2. The major systems are contributed of various components: BIW – cross and side beams, roof, front-end, underbody, passenger compartment frame, and floor; Powertrain – engine, transmission, exhaust, fuel tank; Chassis – chassis, suspension, tries, wheels, steering, brakes; Interior – seats, instrument panel, trim, insulation, air bags; Closures – front and rear doors, hood, lift gate; Miscellaneous – lighting, windows, glazing, thermal, electrical (Mayyas 2012).

The typical vehicle BIW is made up of around 400-500 stamped metal component parts, which are joined together mainly through a spot welding (around 5,000 spot welds per vehicle) process, and then painted (Mayyas 2012). These components can be made of different metals in the same vehicles: different types of steel, aluminium and some small applications in magnesium and carbon fiber.

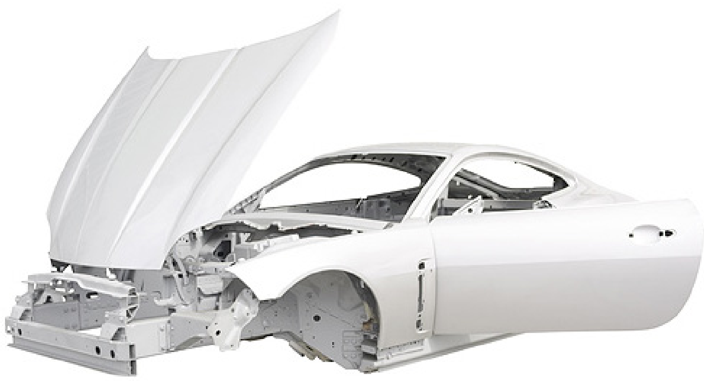

Figure 3 from (IAI 2016)

Steel is the most basic and cheapest option. Aluminium is often regarded as a better alternative, allowing 40% LW on average at a slightly higher cost. While aluminium tends to be widely used in upper segment vehicles, the advantages of LW are undeniable across all segments and powertrains.

Currently, many studies highlight how aluminium usage is a growing trend:

Ducker forecasts a growth in the average aluminium content in European cars (150.6 kg in 2016) of 27.6 - 45.6 kg (18-30%) by 2025.

Global growth is going to be driven mainly by the greater use of flat rolled product, as the closures are increasingly moving towards Al (Ducker Worldwide 2016). Specifically, the hood is often the first element of a car that moves from steel to aluminium, due to both low technical complexity and ideal effects on the center of mass (moved backwards and downwards).

1.4 Limitations of the Study

It must be noted that this study is focused on Global Warming Potential (GWP) of primary aluminium material substitution, and limited in that:

a. The impact of recycling on aluminium or steel life cycle emissions are not addressed

It is well known that there is approximately a 90% emissions reduction in secondary aluminium versus primary aluminium (Liu and Muller 2012), and an 80% reduction in secondary steel versus primary steel (Quader 2015). In the automotive sector, certain parts cannot use secondary aluminium and steel due to quality concerns or use of particular alloys. This means that some components need to be primary aluminium, for example most of the cylinder heads, while less critical ones such as the engine housing are entirely secondary aluminium.

This study uses the methodology of EOL accounting which takes into account the energy used in recycling the vehicle, not crediting aluminium or steel used in the future as a carbon emissions reduction. The purpose of this assumption was to isolate the impacts of the BIW to weight reduction, therefore removing the recyclability benefits of these metals and recovered scrap during processing as outside the scope of this study.

b. It solely focuses on the GWP (CO_2eq) aspect of LCAs

The other aspects such as Total Primary Energy (MJ) & Cumulative Energy Demand (MJ), along with the Acidification, Eutrophication, Photochemical Smog, Respiratory Effects, and Ozone Depletion Potentials were not analyzed.

These aspects are outside the scope of this paper due to the fact that vehicles are regulated in GWP, and any reduction due to LW and carbon footprint of raw materials, are more easily compared on the same scale. For more complete information on primary aluminium life cycle aspects, consult (IAI 2017). Next we address the worldwide aluminium production scenario.

2. Aluminium Industry Emissions Footprint

Global aluminium production uses ~3.5% of global electricity production, and accounts for approximately 1% of global CO_2 emissions (Cullen and Allwood 2013). The aluminium industry resource for emissions data is the International Aluminium Institute (IAI), which provides energy intensity and carbon emissions data for each aluminium-producing country.

As seen in Figure 4, global aluminium smelting energy intensity has been gradually decreasing over the past 10 years of data, decreasing from 15.3 MWh / T Al in 2010 to 14.2 MWh / T Al in 2015 (IAI 2017) - energy efficiency at the smelter being a innovation major focus for producers.

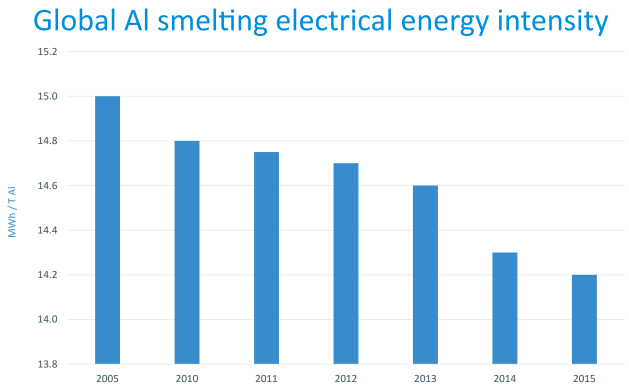

Figure 4 adapted from (IAI 2017)

Due to the lack of global transparency and accurate data of bauxite and alumina production, primary aluminium producers commonly communicate the carbon footprint of primary aluminium based on smelter Scope 1 & 2. To allocate for this difference in the LCA model, we use a definition that low CO_2 Al is < 4 T CO_2 / T Al, smelter Scope 1 & 2 with the addition of the IAI world average data for bauxite and alumina (adding 2.4 T CO_2 / T Al), thus making the full scope number for this study 6.4 T CO_2 / T Al.

It is inferred that low CO_2 Al is produced with hydropower - 27% of worldwide production

with a minimal amount being produced with nuclear and other renewable energies.

Smelter Scope 1 & 2 covers the process emissions (Scope 1) and emissions from energy or heat consumed at the plant (Scope 2). Scope 3 is defined as emissions from raw materials and products used, in this case bauxite mining, transport, alumina refining, caustic soda, etc. (Liu and Muller 2012). Full scope (Scope 1 + 2 + 3) emissions are typically called mine-to-casthouse and are estimated in this study based on IAI data after internal analysis.

To this effect, data from 2015 points to the smelter Scope 1 & 2 global average being 13.4 T CO_2 / T Al, and full scope being 15.8 T CO_2 / T Al (IAI 2017) (Liu and Muller 2012). Full scope emissions are broken up accordingly below, demonstrating that the majority of emissions (78%) occur at the smelter (process emissions, electricity carbon footprint, PFCs, anode production, and ingot casting). The disparate carbon footprints related to primary aluminium production range from 2 – 41 T CO_2 / T Al globally per smelter, full scope (Liu and Muller 2012). Over half (35.7 million Tons, MT) of global capacity is based in China, where 90% of primary aluminium production is coal powered. The other 27.3 MT is distributed among the other regions as shown in Figure 6 (CRU 2017).

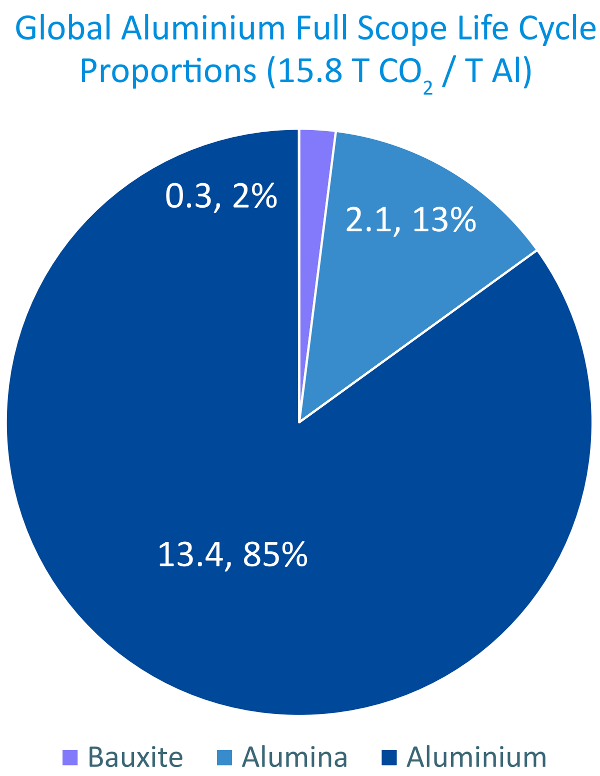

Figure 5 from (IAI 2017)

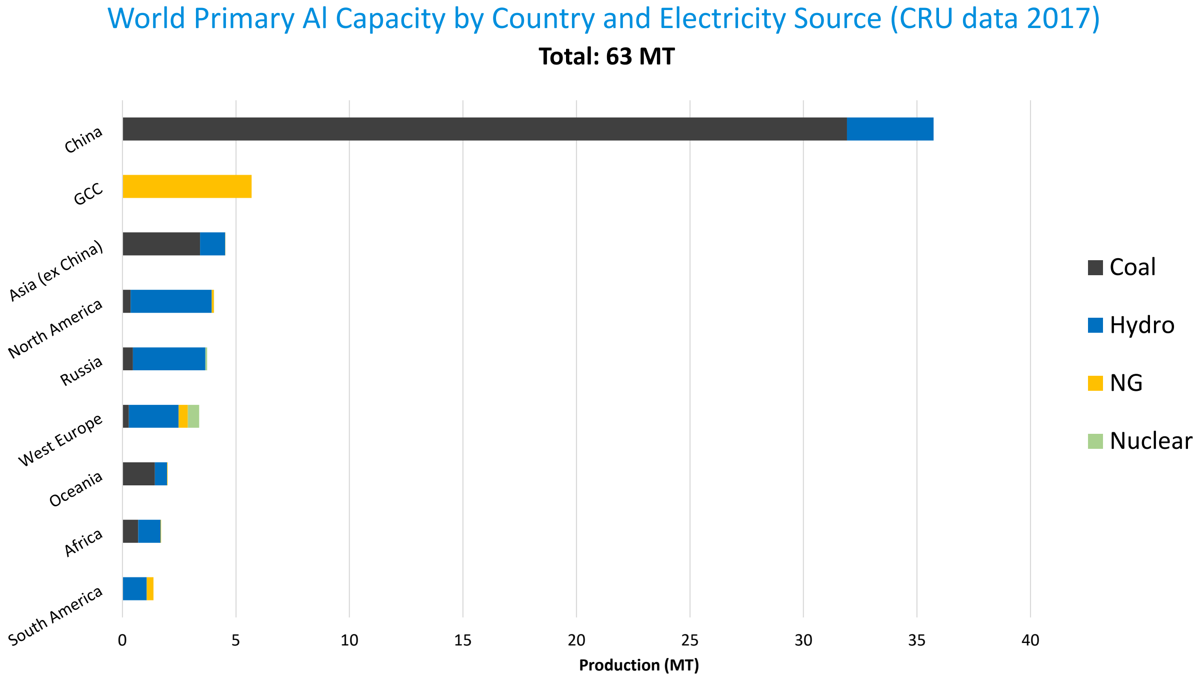

Figure 6 from (CRU 2017) data

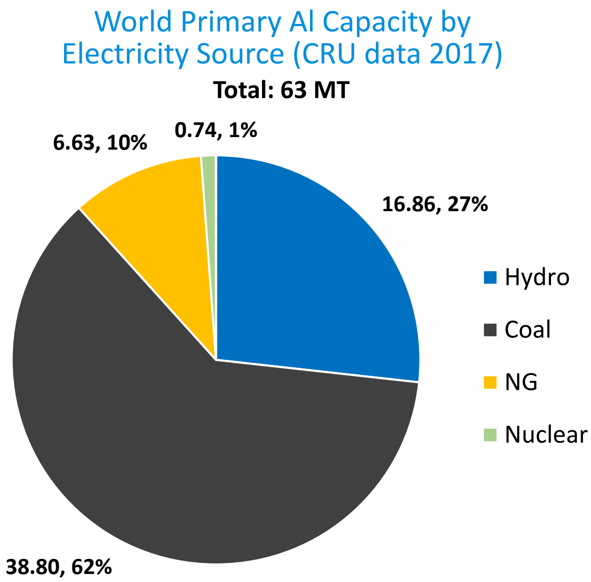

Figure 7 from (CRU 2017) data

The data presents a holistic overview of the energy sources used in the aluminium industry. RUSAL's smelting capacity is almost entirely in Russia, with one smelter operating in Sweden. The dominating energy source for RUSAL's production is hydro-power (> 90% as of 2016), with goals to be at 95% by 2025.

As data on each smelter's emissions data is confidential, we rely on averages provided by IAI of emissions per electricity type, shown below from internal analysis based on (IAI 2017) data. It is interesting to note from Figure 8 that hydro-powered smelters have dramatically lower emissions than coal based smelters – ranging from 2.4 to 16.4 T CO_2 / T Al.

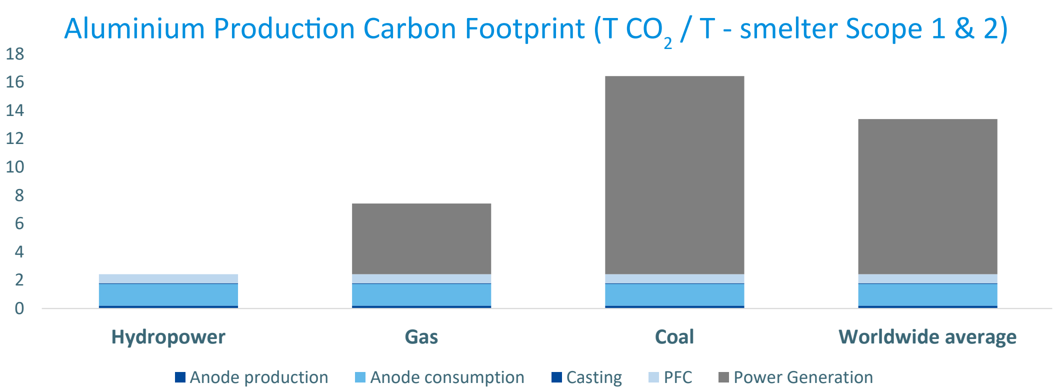

Figure 8 from RUSAL analysis based on (IAI 2017) data

3. LCA Literature Review

3.1 Methods

The life cycle components of vehicles are comprised of: (1) material production, (2) manufacturing, (3) use, and (4) end of life – EOL, as shown in Figure 9. There are several industry models which are typically used for life cycle analysis – in the literature review, two of the most prominent used in European-focused sources in this study is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and the Ecoinvent 3.3 model, along with the US Life Cycle Inventory. The different LCA methodologies present a need to calibrate the results with a standardized set of assumptions.

Many studies focusing on ICEVs tend to focus on a WTW analysis, which just cover the use-phase (versus a full LCA with material production, manufacturing, and EOL). For this analysis, fuel production and vehicle operation were considered as 'use phase'. This number varies for PHEVs and BEVs due to the carbon intensity of the electricity source.

Life Cycle Assessment

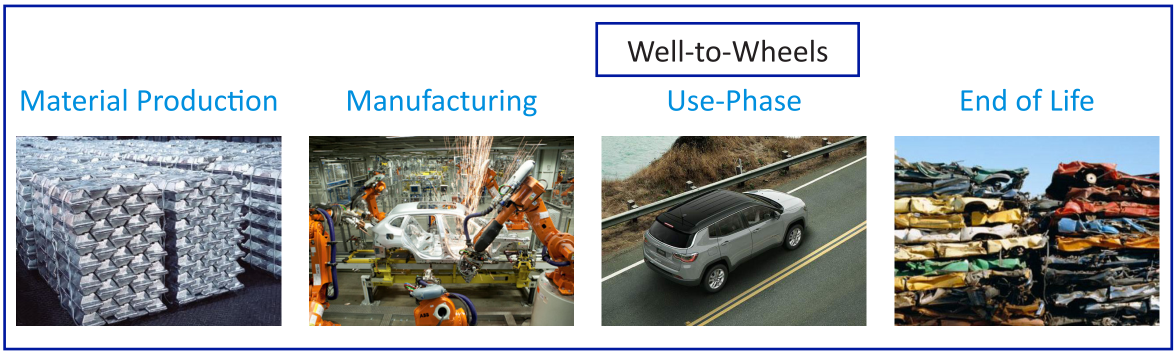

Figure 9. WTW and LCA methodologies.

The 24 LCA studies reviewed had differing assumptions and methods attributing their respective findings. For this study, each source's data was standardized with a unified methodology to deliver a comprehensive review of life cycle emissions different powertrains, varied by car segment. This standardized LCA data could then be used to study the implications of AMS.

Automotive fuel economy standards are typically measured in g CO_2eq / km, but often studies report g CO_2eq / kg vehicle or T CO_2eq over the life of the vehicle. The distance driven over the course of the vehicle life was assumed to be **230,000 km**, an average between the EU (180,000 km) and US (280,000 km) numbers and close to the average discussed in (Hottle 2017). The T CO_2eq life cycle values were then scaled to the contributions per category. All of the LCA studies reviewed used the full scope primary aluminium production world average at the time of data collection, typically between 10-14 T CO_2 / T Al depending on the study year.

Studies that focused primarily on one powertrain type were compared to those analyzing an array of data on car segments, powertrains, and differing geographical driving cycles and electricity mixes. Literature that is non-LCA was used to provide necessary information to analyze the research question in the context of AMS. Most studies were in peer-reviewed journals or national laboratory/institute reports, with all but four studies published after 2010. Steel was always the baseline metal, with various materials being used as substitutes, predominantly aluminium, AHSS, and magnesium.

The 24 studies analyzed covering LW & LCA for ICEVs, PHEVs, and/or BEVs are listed in Table 1.

First Author	Year	Publication	Country / Affiliation	ICEV	PHEV	BEV
Audi	2016	Self-published	Germany / Self	x		x
Chanaron, J.	2007	Int. Journal of Product Lifecycle Mngmt.	France / University	x		
Cheah, L.	2010	PhD Dissertation (MIT)	USA / University	x	x	x
Das, S.	2014	SAE International Journal	USA / Nat. Lab.	x		
Ellingsten, et al.	2016	Environ. Res. Lett.	Norway / University	x		x
Hawkins, et al.	2012	Journal of Industrial Ecology	Norway / University	x		x
Helms, et al.	2010	Int. Symp. Transport and Air Pollution	Germany / Institute		x	x
Hottle, et al.	2017	Transportation Research	USA / Nat. Lab.	x	x	x
Kim, H.J., et al.	2010	Journal of Industrial Ecology	USA / University	x		
Kim & Wallington	2016	Environ. Sci. Technol.	USA / Ford	x	x	x
Kim & Wallington	2013	Environ. Sci. Technol.	USA / Ford	x		
Lewis, et al.	2014	Journal of Applied Energy	USA / University	x	x	x
Mayyas, et al.	2012	Journal of Energy	USA / University	x		
Modaresi, et al.	2014	Environ. Sci. Technol.	Norway / University	x		
Orsi, et al.	2015	Journal of Applied Energy	USA / University	x	x	x
Poulikidou, et al.	2015	Materials & Design	Sweden / University	x		
Samaras, et al.	2008	Environ. Sci. Technol.	USA / University	x	x	x
Stodolsky, et al.	1995	Argonne National Laboratory	USA / Nat. Lab.	x		
Sullivan, et al.	2010	Argonne National Laboratory	USA / Nat. Lab.	x	x	x
Tagliaferri, et al.	2016	Chemical Engr. Research and Design	UK / University	x	x	x
Toyota	2015	Self-published	Japan / Self	x	x	
Ungureanu, et al.	2007	Minerals, Metals, & Materials Society	USA / University	x		
van Vliet, et al.	2010	Journal of Power Sources	Austria / Institute	x	x	x
Wang, et al.	2013	Journal of Energy	China / University	x	x	x

Table 1. Selected LCAs for vehicle mass reduction.

3.2 BIW Analysis

After standardization of driving distances to 230,000 km, GHG reporting and other LCA methodologies, life cycle stage contributions were produced from average T CO_2eq emissions between segments A - F, as demonstrated in Figure 10 and Figure 11 for ICEVs and BEVs, respectively. These average contributions include data from passenger vehicles of all classes. PHEVs demonstrated a similar breakdown to ICEVs, but due to their larger battery, have slightly lower material production emissions (14%), higher manufacturing emissions (9%), lower use-phase emissions (73%), and similar EOL emissions (4%) – with total life cycle emissions of **46.3 T** CO_2eq (**147 g / km** use-phase).

Note that the BEV use-phase emissions are based on the average European electricity mix in 2015, with a carbon intensity of 0.521 T CO_2 / MWh. This is based on a mix of 29% renewables, 28% nuclear, 25% coal, 16% natural gas, 2% oil (Ellingsten 2016).

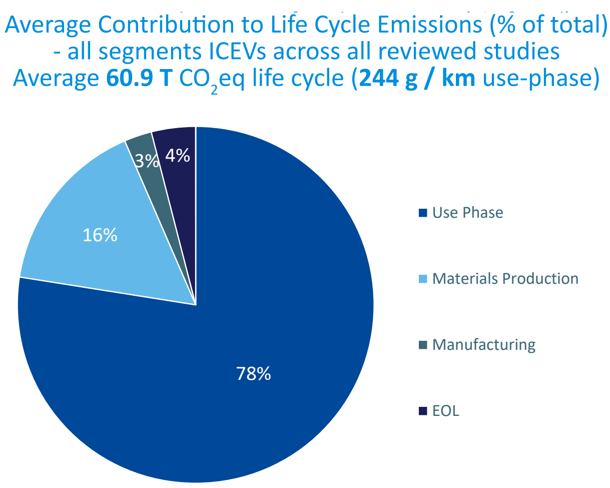

Figure 10

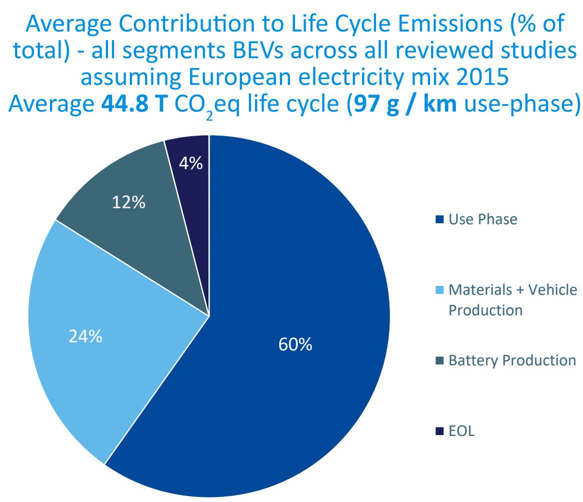

Figure 11

It can be seen that materials and vehicle production, along with battery production, play a much larger role in a BEV's life cycle contributions compared to ICEVs. Although it was difficult to parse out manufacturing from the materials and vehicle production section of BEVs, it is known that OEMs are strongly focusing on LW to improve the range of their BEVs. This should lead to a split incentive as OEMs are regulated on fuel efficiency and carbon emissions on a g CO_2eq/ km basis – they can LW ICEVs to directly improve emissions and range, but LW a BEV does not always directly improve emissions. In some countries` regulation, BEV emissions are counted as 0 g CO_2eq/ km, not incorporating the grid carbon intensity. In this case, LW does not improve further the vehicle efficiency and only has a positive effect on the vehicle range. Under such regulation, the positive impact of LW on emissions does not exist anymore.

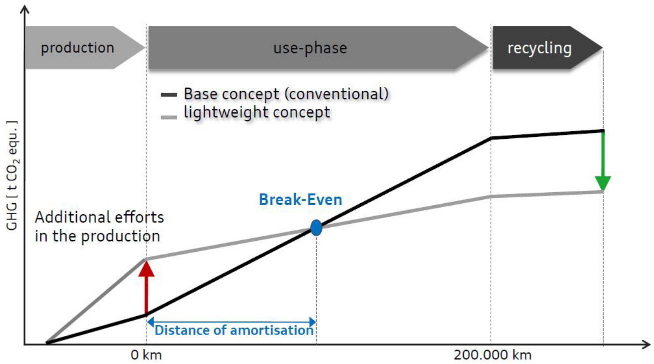

Figure 12 taken from (Seifert 2017)

Many studies evaluated or provided data in order to calculate breakeven driving distances (carbon paybacks) of LW and AMS, with a general depiction of using higher energy intensive materials (aluminium, AHSS, carbon fiber, etc.) to achieve lower use-phase emissions shown in Figure 12. The green arrow represents the net savings of GHG over the vehicle life cycle.

To begin, in (Kim and Wallington 2013), a comprehensive literature review of 43 LW-focused automobile LCA studies with a similar scope to this paper in its standardization methodologies, found that all reviewed studies indicated that using aluminium, AHSS, and carbon fiber to replace conventional steel decreases vehicle life cycle energy use and GHG emissions.

Further, a clear pattern from the reviewed 24 LCA studies showed that out of all the BIW material substitutes for steel, the aluminium's carbon footprint contribution to a vehicle's material production emissions has the highest life cycle sensitivity in terms of LW payback. In other words, due to aluminium's high energy production demand (correlating with higher CO_2eq emissions) and significant LW potential, reducing aluminium's production emissions can have the highest potential to reduce overall vehicle life cycle emissions among all substitutive materials. Even though magnesium and carbon fiber are lighter than aluminium, their energy (and emissions) intensive production does not offer attractive carbon paybacks compared to aluminium (Das 2014) (Kim and Wallington 2013) (Lewis 2014) (Mayyas 2012) (Modaresi 2014) (Poulikidou 2015) (Ungureanu 2007) (Wang 2013).

In summary, the above studies all found that replacing a steel BIW with an Al-Intensive BIW has the highest potential to decrease vehicle life cycle emissions, of all LW materials.

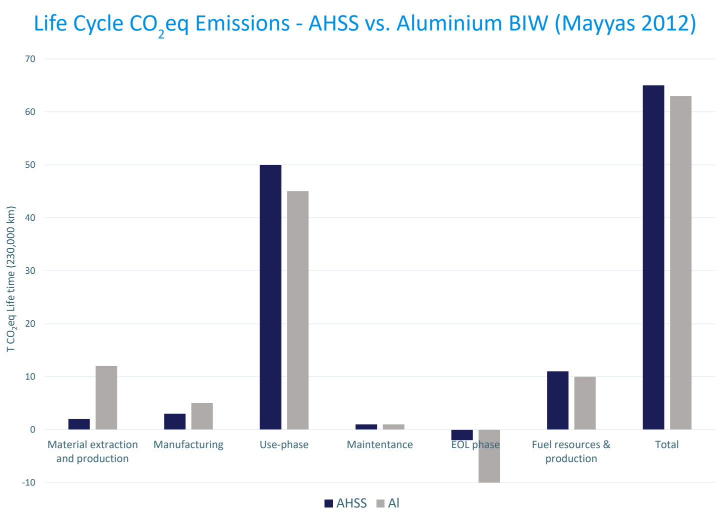

Figure 13 from (Mayyas 2012) data

These studies compared various LW BIWs to a baseline steel BIW, assuming a world average aluminium carbon intensity (varies by study year). Figure 13 provides an example ICEV life cycle with AHSS vs. Al-Int BIWs from (Mayyas 2012). Although the AHSS BIW has much lower material production emissions compared to world average primary aluminium, the initial material production emissions pay back (similar to Figure 12) during the use-phase and recycling components, with a total **3.1%** improvement.

The attractive carbon payback of Al-Intensive vehicles would be further improved with low CO_2 footprint primary aluminium, as the material extraction and production emissions would be below 6.4 T CO_2 / T Al, compared to the 12 T CO_2 / T Al world average presented in (Mayyas 2012). This will be analyzed in detail further in section 5 - Advantages of Low Carbon Aluminium.

It must be stated that due to aluminium's high recyclability emissions savings versus steel, there are significant life cycle impacts upon crediting the recycled aluminium (EOL phase), as it would avoid future use of primary aluminium. Exemplified in (Mayyas 2012) is the EOL crediting methodology, but this is not addressed in this study's model to keep a conservative perspective on EOL recycling as discussed in the limitations of this study in section 1.4.

3.3 Powertrain Analysis

This study aims to parse out the life cycle emissions between various powertrains – ICEVs, PHEVs, and BEVs. The life cycles of Hybrids, Fuel Cell Vehicles, and Compressed Natural Gas (CNG) vehicles were not considered in this study. There was not enough literature for a complete LCA literature review of Fuel Cell Vehicles and CNG vehicles. Hybrids presented life cycle footprints and contributions between ICEVs and PHEVs, and due to this study's focus on electricity mix carbon intensities, PHEVs were chosen.

BEVs are considered to have higher material production and manufacturing emissions than ICEVs and PHEVs due to intensive and larger battery production. Many studies 'baked' these two LCA components together, but it is considered that BEVs have 2-3 times of the absolute material production and manufacturing emissions than ICEVs (Tagliaferri 2016).

If BEVs are entirely powered by renewable sources during their use, it is intuitive that almost their entire footprint will be from material production and manufacturing emissions.

Factories such as BMW's i3 manufacturing facility in Leipzig are going renewable, further lowering the manufacturing (and assembly) footprint of their vehicles (BMW). With energy mixes that are not dominated by coal, BEVs already have lower life cycle emissions than ICEVs, and will continue to improve with 'greener' material production.

The current carbon intensity of European and US mixes (2015 data) conclude that PHEVs often have only slightly higher life cycle emissions with BEVs of the same class, even with life cycle contributions similar to ICEVs - characterized by 70-80% of emissions coming from the use-phase (Ellingsten 2016) (Hawkins 2012) (Helms 2010) (Lewis 2014) (Samaras and Meisterling 2008) (van Vliet 2010). Further, as BEVs increase in size, the 'size and range effect' shows that the larger battery production emissions and use-phase energy requirements dramatically increase the life cycle GWP, by 70% between BEVs of segments A and F (Ellingsten 2016).

The carbon paybacks between BEVs and ICEVs show a similar pattern as the 'size and range effect' due to higher battery production impacts of similar segment vehicles - with paybacks between 44,000 km (segment F) and 70,000 km (segment A) respectfully. BEVs were found to have a 20-27% lower life cycle emissions than ICEVs for C-segment vehicles (Ellingsten 2016) (Hawkins 2012). In summary, BEV life cycle emissions are highly sensitive to battery size.

Further, the carbon-intensity of the electricity mix dramatically impacts these paybacks. For example, (Orsi 2015) shows that BEVs & PHEVs in China have higher use-phase (g CO_2eq / km) emissions than HEVs and are very close to the footprint of CNG vehicles, due to the coal-heavy grid (72%). This is a surprising finding considering that 22% of China's grid is renewable (EIA

2017). The pattern is otherwise the same – as long as the electricity mix is not majority coal, even if it is majority natural gas, there will be an attractive carbon payback for electrification; as shown in four studied nations - Brazil, France, Italy, and the US (Ellingsten 2016) (Orsi 2015).

4. LCA Model Results

After the LCA literature review, a market analysis was done on three car segments – A, C, and E – to model the primary and secondary aluminium content of an Al-Intensive vehicle over various powertrains. One of the limitations of this study is lack of sensitivity analysis on primary vs. secondary steel material production emissions impacts - this is an area to explore for future research. The steel vehicle data was based on findings from the standardized literature review. Actual vehicle specifications and data were gathered for the three segments on the VW Polo 2017, Skoda Kodiak 2016, and the Audi A8 2017, respectively. The specifications were then modified in order to obtain standardized vehicles - each car model has a unique breakdown of body materials that makes it impossible to draw meaningful comparisons.

Therefore, for this study it was considered that an Al-Intensive vehicle has all closures and half of the BIW made of aluminium, a composition that is much alike that of the Audi A8 2017 (original 1,995 kg, already Al-Intensive); the VW Polo 2017 (original 1,033 kg, 16% lighter with Al-Int) and the Skoda Kodiak 2016 (original 1,527 kg, 15% lighter with Al-Int) were then modeled to reflect the Al-intensive part-by-part composition breakdown, shown in Table 2. The model uses a replacement ratio of 1 kg Al to 1.4 kg steel.

Further, although the vehicles are all ICEVs, their BIW and powertrain material compositions were then modelled to reflect BEVs and PHEVs with a detailed part-by-part configuration of aluminium and steel components. With the detailed material composition data, the model was able to characterize the life cycle GWP impact of substituting 'world average' carbon intensity aluminium (15.8 T CO_2 / T Al) for full scope low CO_2 aluminium (6.4 T CO_2 / T Al). While it would have been possible to consider actual vehicles for each powertrain type, their design and material composition would have been different and therefore it would not have been possible to compare them accurately one to one. Modelling BEVs and PHEVs based on actual vehicle component representations of specific segments allows the exclusion of other variables in order to isolate the powertrain differences.

Powertrain	Segment	Primary Al (kg)	Secondary Al (kg)	BIW weight (kg)	Total weight (kg)	Car model
ICEV	ICEV A	202	31	196	871	Modeled VW Polo 2017
	ICEV C	273	56	273	1305	Modeled Skoda Kodiak 2016
	ICEV E	323	125	282	1995	Modeled Audi A8 (actual weight)
BEV	BEV A	191	15	196	1215	Modeled VW Polo 2017
	BEV C	272	22	273	1649	Modeled Skoda Kodiak 2016
	BEV E	359	58	282	2339	Modeled Audi A8
PHEV	PHEV A	193	46	196	991	Modeled VW Polo 2017
	PHEV C	269	72	273	1425	Modeled Skoda Kodiak 2016
	PHEV E	326	143	282	2115	Modeled Audi A8

Table 2. Modeled Al compositions of modeled Al-intensive vehicles.

The contributions of primary aluminium to the vehicle's life cycle GWP were then evaluated with data from the standardized literature review. The theoretical life cycle emissions impacts of an Al-Intensive vehicle between powertrains and segments was calculated, modelled on real data. Our model demonstrates that an Al-Int vehicle will have **12.6%** lower life cycle emissions than a baseline steel ICEV (C-segment), a conservative figure in light of the findings from the literature review, shown in Figure 14. The carbon payback occurs at **63,300 km** (Figure 15).

Aluminium-Intensive Vehicle in Comparison to Baseline Steel Vehicle (C-segment)

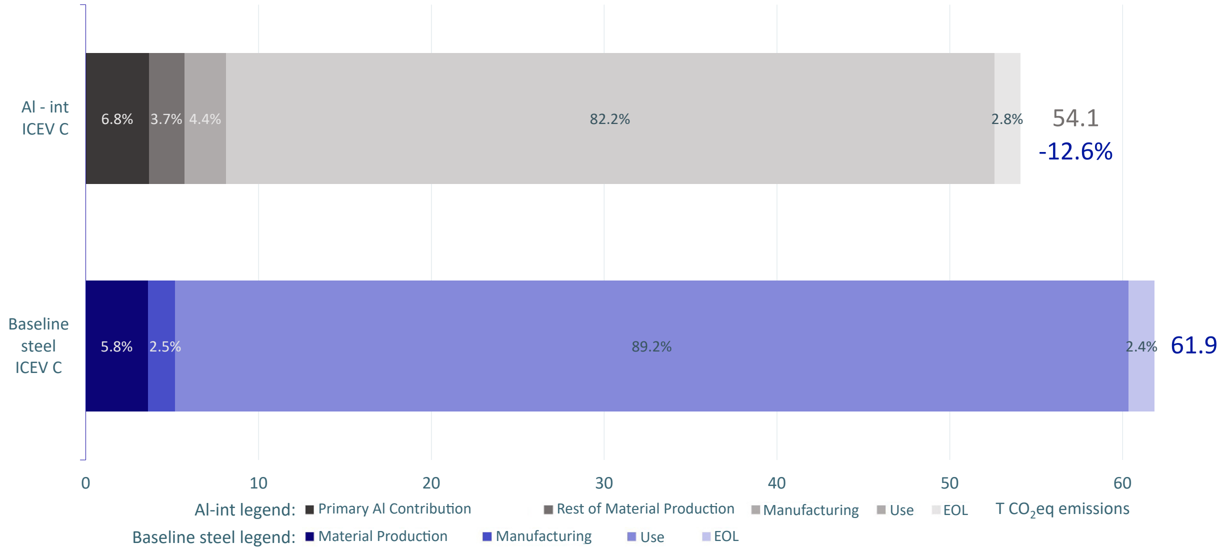

Figure 14

Carbon Payback of ICEV Baseline Steel and ICEV Al-Intensive BIW

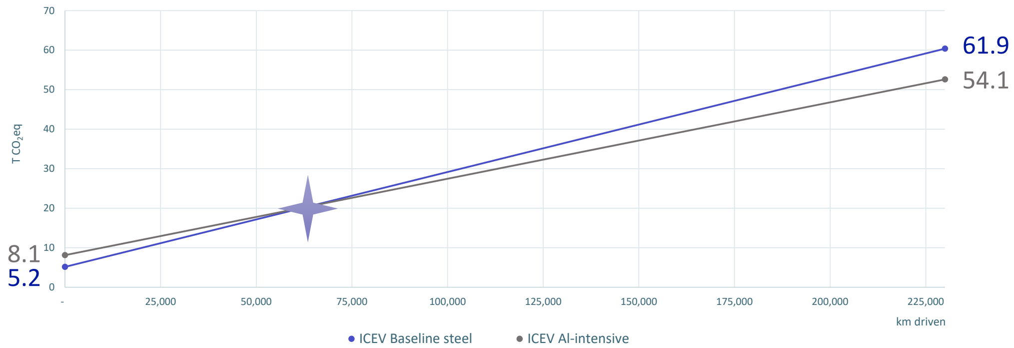

Figure 15

Comparing BEVs of various power mixes (European, coal-heavy, and wind-heavy) in Figure 16 shows that compared to the PHEV, the wind-powered BEV achieves a payback of **86,600 km.** If it is powered by the European-mix, it achieves a payback at **144,800 km**.

It is interesting to note that while the current carbon intensity of the European grid positions a BEV to be **11.2% better** on a life cycle GWP perspective than a PHEV, the payback period compared to the Al-Int vehicle is shorter for a PHEV (**63,900 km**) than with a BEV European-mix (**108,700 km)** due to the PHEVs lower material and manufacturing emissions.

Carbon Payback of Al-Intensive ICEV, BEVs, and PHEV

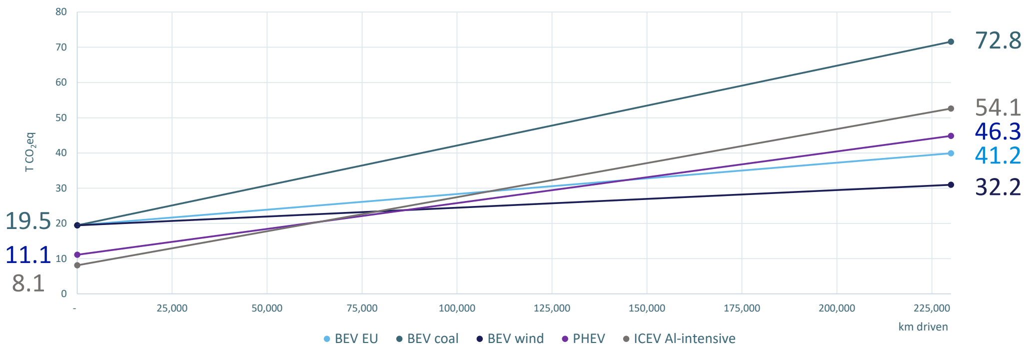

Figure 16

From a fuel regulation standards perspective (g CO_2eq / km), the impacts of the electricity mix carbon intensity and of substitutive materials can be seen in Figure 17. It is shown that a coal powered BEV would be **18%** worse than the baseline steel ICEV, confirming the China findings from (Orsi 2015). Note that for BEVs, battery production is included in the manufacturing component in many studies. The use-phase values were scaled from the T CO_2eq life cycle.

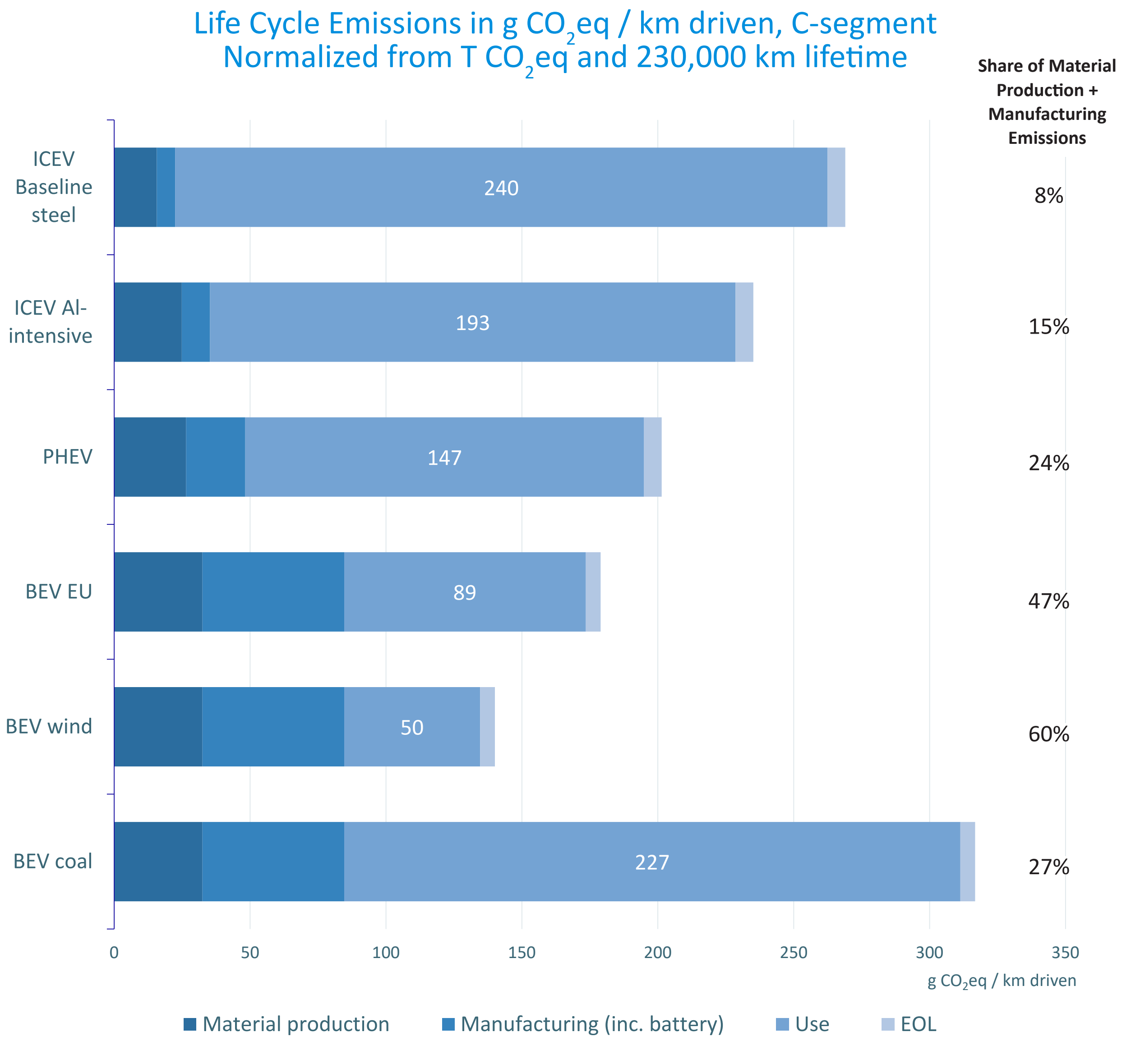

Figure 17

A wind-powered BEV's use-phase drops to **36% of total emissions**, leaving materials and manufacturing (inc. battery) as the majority of environmental impact (**60% of total**).

The carbon paybacks to an Al-Intensive vehicle (and Baseline steel) is as follows:

BEV wind - **79,200 km** (75,300 km)

BEV European – **108,700 km** (94,700 km)

PHEV – **63,900 km** (63,600 km)

5. Advantages of Low Carbon Aluminium

Figure 18 demonstrates the opportunity for a low carbon footprint primary aluminium to benefit Al-Intensive vehicles by powertrain. Using low CO_2 Al (6.4 T CO_2 / T Al) vs. world average (15.8 T CO_2 / T Al) full scope can significantly impact the life cycle emissions of Al-Intensive vehicles from **4.7 to 6.2%** depending on the powertrain.

For the C-segment ICEV (**4.7%**) decrease, this accounts for a **2.6 T** CO_2 difference over the life time of the vehicle reflected in the primary aluminium contribution reduction. Using this vehicle's use-phase emissions (193 g CO_2eq / km), this would equate to approximately **13,500 km** 'not driven' during the lifetime.

This truly is a 'Gigaton solution' (Modaresi 2014) – that it will take slightly over 4 years of current light duty vehicle production levels to reach a one billion Ton CO_2 impact. For reference, that equates to 385 million passenger cars going Al-intensive with low CO_2 aluminium. There were ~90 million light duty vehicles produced in 2016 alone (IHS 2015).

For BEVs, this reduction can be even more dramatic (**6.2%**) as raw materials emissions make up a larger part of the life cycle picture, especially if powered by renewables.

Note that secondary aluminium contribution is not shown on the graph, with a value < 0.2 T CO_2 over the lifetime for each vehicle segment due to the EOL accounting method used.

Low CO_2 Primary Aluminium Life Cycle Value in Comparison to Al-Int Vehicles (C-segment)

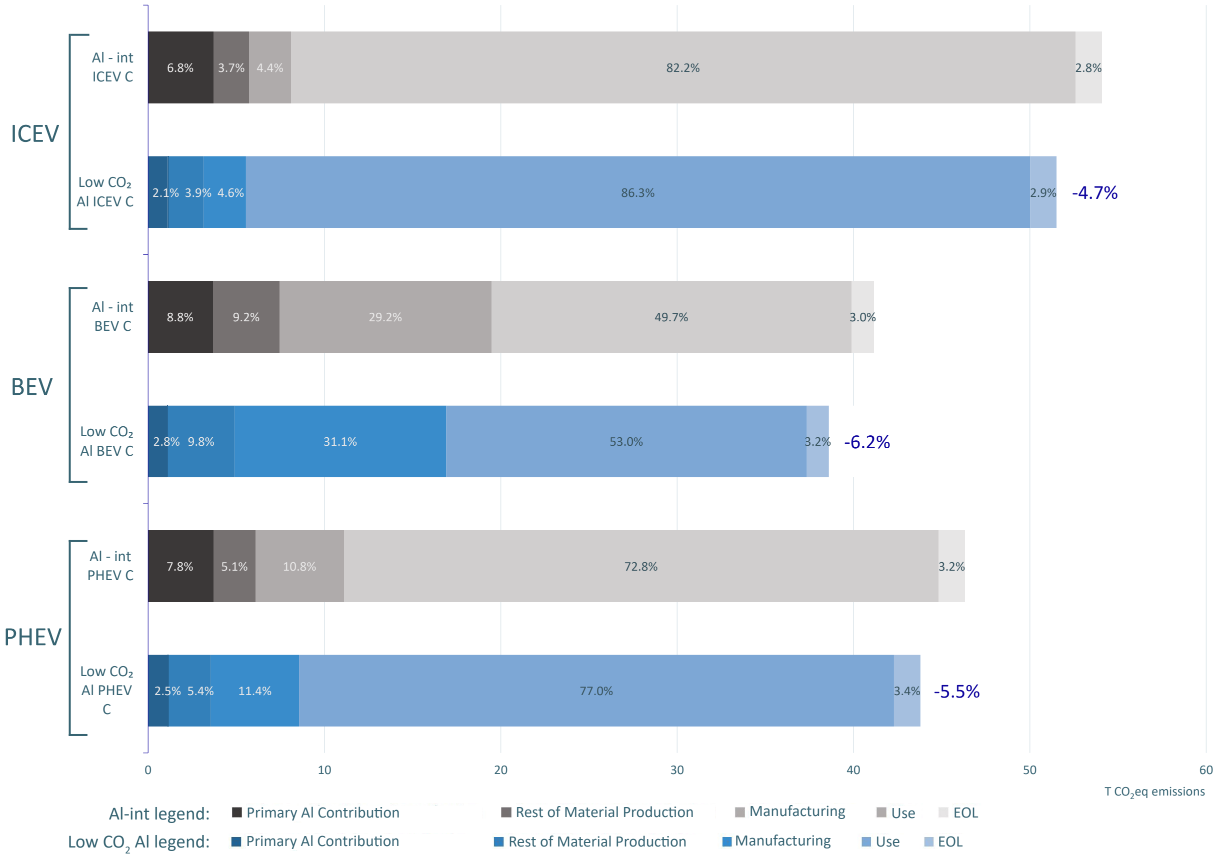

Figure 18

The C-segment low CO_2 Al-Int ICEV can have a **17%** lower carbon footprint through its life cycle (**10.3 T** CO_2) versus the baseline steel vehicle, as shown in Figure 19. The carbon payback for the slightly higher material production emissions (0.4 T CO_2) is just **8,400 km**, a significant improvement to the worldwide average Al-Int vehicle payback vs. baseline steel of 63,300 km, a difference in carbon payback of **54,900 km**.

In order to reach a payback of 0 km (equal material production emissions for a functional unit of steel vs. lighter aluminium) the primary aluminium material production emissions would need to be below 3.4 T CO_2 / T Al, full scope. This assumes this study's material replacement ratio and full scope production footprints for both materials.

Low CO_2 Primary Al-Int ICEV in Comparison to Baseline Steel ICEV (C-segment)

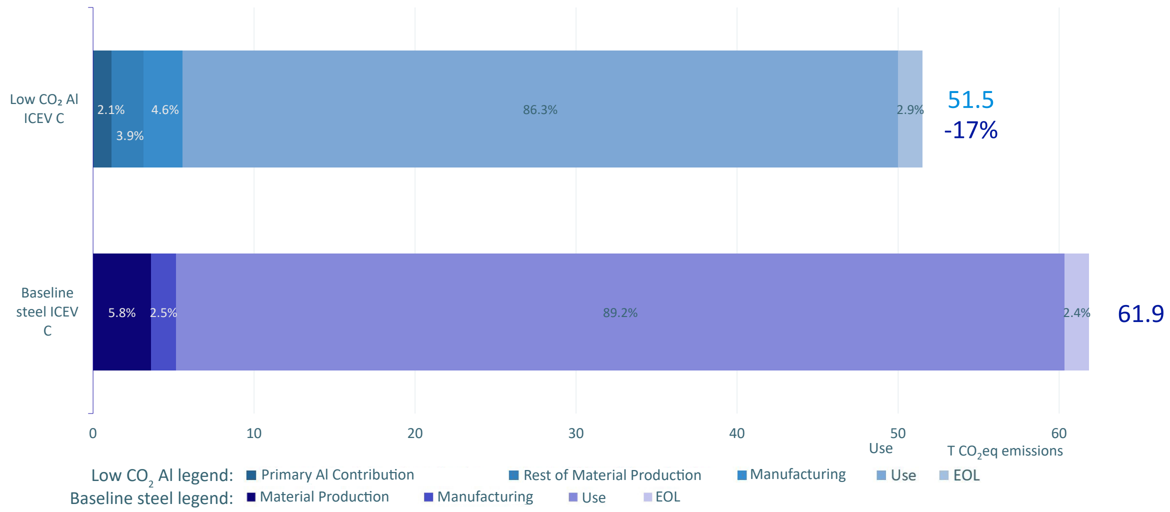

Figure 19

Carbon Payback of Baseline Steel ICEV and Low CO_2 Primary Al-Int ICEV (C-segment)

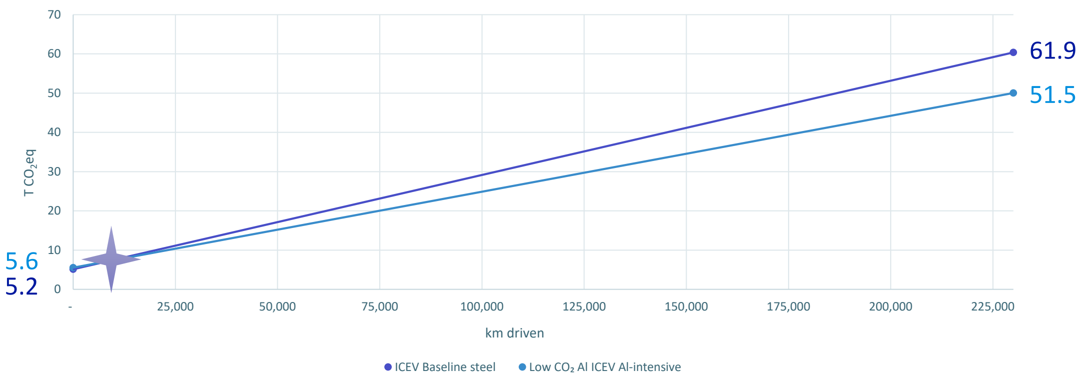

Figure 20

The life cycle emissions advantages of aluminium LW for passenger vehicles have been shown from the LCA vehicle model based on reviews of industry and academic sources. OEMs already consider LW as a way to reduce the use-phase emissions of their vehicles (g CO_2eq / km) in order to meet each country's stringent fuel economy goals by 2025. This paper argues that OEMs must also use low CO_2 footprint materials in order to achieve greater CO_2 reductions.

The data presented shows an opportunity for OEMS to choose the most effective LW material possible - a low CO_2 Al-Intensive vehicle - on any powertrain. This is necessary to avoid 'shifting' the environmental burden to other sectors by replacing the historically baseline steel BIW with materials that are more than just lighter, but lower carbon footprint on a life cycle GWP basis.

6. Conclusion

This study has presented a lightweighting (LW) and aluminium material substitution (AMS) vehicle model based on an in-depth life cycle analysis (LCA) literature review which will guide car manufacturers to incorporate raw material carbon footprints in vehicle production. It is clear that a low CO_2 Al-Intensive vehicle demonstrates the most attractive carbon payback over the life cycle for every vehicle segment and powertrains studied.

The future of passenger vehicles on any powertrain necessitates rapid improvements in fuel efficiencies and use-phase emissions (g CO_2eq / km) to meet the aggressive national targets across many industrialized nations. Future environmental and efficiency standards relating to vehicle emissions should also discern the raw material production carbon footprints – what matters is the overall life cycle carbon footprint of the vehicle in terms of T CO_2eq, not simply the use-phase as currently regulated.

As ICEVs become lighter and more fuel efficient, the share of BEVs and PHEVs grows, and renewable electricity production increases - the overall life cycle footprint of passenger vehicles will dramatically decrease and the CO_2 emissions embedded in raw materials will become more prominent in proportion.

The results shown here conclude that (compared to baseline steel BIW C-segment):

a. **The use of aluminium in BIWs and closures (Al-Intensive) reduces life cycle emissions by 12.6% (7.8 T CO_2) for ICEVs – the carbon payback occurring at 63,300 km.**

b. **Low CO_2 Al produced with hydropower further reduces raw material emissions with a total savings of 17% (10.3 T CO_2) for ICEVs – the carbon payback is dramatically reduced to just 8,400 km.**

c. **BEVs are more sensitive to the carbon footprint of their raw materials compared to ICEVs. Low CO_2 Al further reduces the carbon payback of a European energy mix BEV by 16,900 km.**

d. **Lightweighting with low CO_2 Al is a Gigaton CO_2 reduction solution – 4.7% , 5.5% , 6.2% decreases in life cycle emissions compared to an Al-Intensive vehicle on all powertrains (ICEV, PHEV, BEV).**

Life cycle analyses play an important role in guiding car manufacturers to develop the fleet of the future. With this knowledge, car manufacturers and regulators will be able to address the need for initiating regulations which take into account the carbon emissions of raw materials in passenger vehicles.

Consequently, the use raw materials with higher carbon footprints could lead to suboptimal life cycle improvements in vehicles, even with use-phase improvements gained through LW.

Low CO_2 aluminium presents the most attractive life cycle CO_2 savings of any vehicle BIW or closure raw material, amplifying the benefits of lightweighting with aluminium.

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Acknowledgements

This study would not have been possible without the help of Marco Luzi of the automotive marketing team at RUSAL, providing valuable insight into the automotive industry in order to develop the part-by-part vehicle model and complete the LCA.

Jerome Lucaes provided valuable guidance and review throughout the research, modelling, and writing process. His insight into life cycle analysis inspired this paper.

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About RUSAL

RUSAL is a leading, global aluminium producer. The company's main products are primary aluminium, aluminium alloys, foil and alumina. RUSAL is a completely vertically integrated aluminium company with assets right through the production process – from bauxite and nepheline ore mines to aluminium smelters and foil mills. RUSAL has a unique position in the aluminium industry as it produces over 90% of its entire aluminium output with renewable hydropower, which makes RUSAL the largest producer of hydro-powered aluminium worldwide.

In a carbon-constrained world, low CO_2 aluminium from RUSAL, known as ALLOW, enables our customers to contribute to their climate change strategy. ALLOW aluminium is made from renewable hydropower and it enables our customers to deliver products with a lower CO_2 footprint to make a positive impact for society.

RUSAL supports global action to prevent climate change and stop global warming. We are firmly convinced that, as an industry leader, we are responsible for shifting commodity paradigms and supporting our customers and partners transition to a low carbon future.

RUSAL