Carbon Footprint of Magnesium Production and its Use in Transport Applications

- Summary -

DLR

Title	Update of Life Cycle Assessment of Magnesium Components in Vehicle Construction
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1 Motivation and Goal

Finding new lightweight solutions is one of the major tasks that the automotive industry is addressing for various reasons. Apart from reducing the vehicle's energy consumption, the increase of electrical mileage is a further motivation in case of electric vehicles. Magnesium is one of the materials which offer advantages as a lightweight material for many transport applications. In order to assess the potential environmental benefits of magnesium, to show the status and progress of different production routes to manufacture magnesium and magnesium alloys and to compare these with each other and with competitive lightweight materials, the International Magnesium Association (IMA) initiated a study on the life cycle assessment of magnesium that was published in 2013. The study "Life Cycle Assessment (LCA) of Magnesium Components in Vehicle Construction" was written by the Institute of Vehicle Concepts of the German Aerospace Centre (DLR) and analysed the entire life cycle of magnesium components for transport applications (Ehrenberger, Dieringa, and Friedrich 2013). Environmental concerns of the production, alloying, components production and use of magnesium were addressed as well as the end-of-life of magnesium components (Figure 1). Since the magnesium production and especially the Pidgeon process in China are subject of continuous improvements, an update of the LCA study reflecting the carbon dioxide (CO_2) and greenhouse gas (GHG) emissions of the current production situation is presented in this update of the 2013 study. The key changes of this update address the following aspects:

- The focus is on the update of the data on the Pidgeon process. Main changes of the Pidgeon process affect the energy sources of the plants, the amount of energy needed and the upstream processes for China specific energy supply. Additionally, the energy supply and direct emissions of the ferrosilicon (FeSi) production are updated.
- Information on the CO_2 balance of alternative existing and of newly planned magnesium production processes is included in this analysis.
- For the magnesium end-of-life phase, additional information on the recycling rate of post-consumer magnesium scrap as well as data on the secondary magnesium production is included.
- A comparison of an automotive and an aircraft part with a reference part made of aluminum is presented in this study in order to show how the magnesium source influences the results on greenhouse gas emissions.

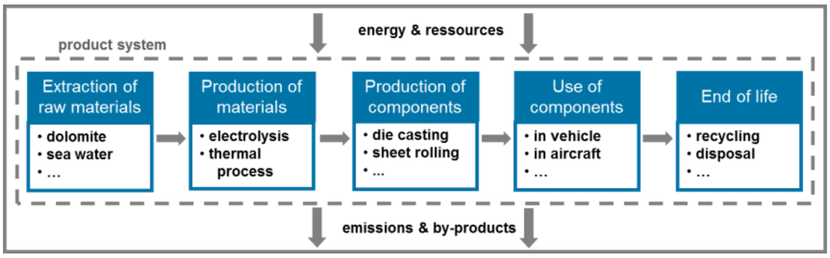

Figure 1: Overview of magnesium life cycle for transport applications analysed in the LCA study in 2013 (Ehrenberger, Dieringa, and Friedrich 2013)

Concerning the applied methodology, the study follows the standards for life cycle assessment DIN EN ISO 14040 and 14044 (ISO 14040 2006; ISO 14044 2006). The results of this study are available to all interested parties. Above all, the study intends to provide up-to-date and reliable data and results on magnesium production. The results of the magnesium production evaluation can be used for any magnesium product as it is not part specific. In general, the user of this study needs to bear in mind that the LCA methodology is an estimate of environmental impacts and the results have to be interpreted as potential impacts rather than predictions on environmental burdens or risks.

2 Analysis of Primary Magnesium Production

Pidgeon Process in China

In the past years since the 2013 LCA study has been published, the Pidgeon process has been further improved. Major efforts have been made to improve the energy efficiency of the process, e.g. by waste heat utilization. Furthermore, stricter requirements concerning the reduction of air pollutants forced the magnesium producers to install additional equipment for air purification. This leads to higher electricity demand for the peripheral equipment and partly compensates for the efforts of energy savings in the reduction process.

The fuel gases used by the various Pidgeon process plants are defined as follows (Ehrenberger, Dieringa, and Friedrich 2013): Producer gas (made in dedicated gas plants for magnesium smelters), coke oven gas (from coking plants), semi-coke oven (from semi-coke plant) and natural gas. The data on the energy consumption of the Pidgeon process has been surveyed by CMA and represents the state of Pidgeon process in 2019. Compared to the data of the 2013 LCA study, the use of semi coke oven gas has increased from 45 % to 64 %. The share of producer gas has decreased from 34 % to 22 % and from 14 % to 6 % in case of coke oven gas. Though the overall amount of magnesium produced with natural gas increased from 43 kt in 2011 to 75 kt in 2019, its relative share remains almost constant at a low level of 8 % (compared to 6 % in 2011). The average consumption of fuel gas as well as other production materials is calculated according to the number of companies without considering the individual production volume of the respective companies.

The emissions of the FeSi production are subject of uncertainty. Due to the nature of the process, certain amounts of CO_2 and CO (carbon monoxide) are released during production. The data for the direct emissions of FeSi production have been updated using data provided by Kero (2017). Furthermore, current FeSi production in China largely takes place in regions with CO_2 intensive electricity supply. Directing attention to a low carbon supply chain would further reduce the overall emissions of the magnesium production (Ehrenberger and Brost 2015).

Results for Greenhouse Gas Emissions

The calculation of the greenhouse gas emissions of the Pidgeon process includes all upstream processes like FeSi or fuel gas production. The production of FeSi, the calcination of dolomite and the reduction itself remain the most GHG-emission intensive life cycle steps. Emissions of FeSi production amount to 12.5 kg CO_{2eq} per kg magnesium. Results for the calcination process vary from 6.7 to 9.1 kg CO_{2eq} / kg Mg depending on the energy source used. Due to the reduced energy consumption, the emissions of the Pidgeon process are lower than in 2011. The overall average emissions of the current process amount to 28 kg CO_{2eq} including all upstream processes. The calculation of the life cycle inventory is based on an allocation for the production of coke oven gas and semi coke oven gas according to the energy contribution of the fuel gases to the entire production from the (semi) coke plant. As at present, these fuel gases are provided to the magnesium producers either for free or at low prices, the gas which would be otherwise released to the atmosphere without use and can be credited to the magnesium production. In this case, the production of these fuel gases is not part of the magnesium production system. The coke production which is an upstream process for the FeSi production is burdened with the full environmental loads in this scenario. When applying this crediting method to the emissions, the weighted average emissions of the Pidgeon process from a cradle to gate perspective amount to 21.8 kg CO_{2eq} per kg magnesium. The direct emissions of the Pidgeon process steps amount to 12.1 kg CO_{2eq} per kg of primary magnesium (Figure 2).

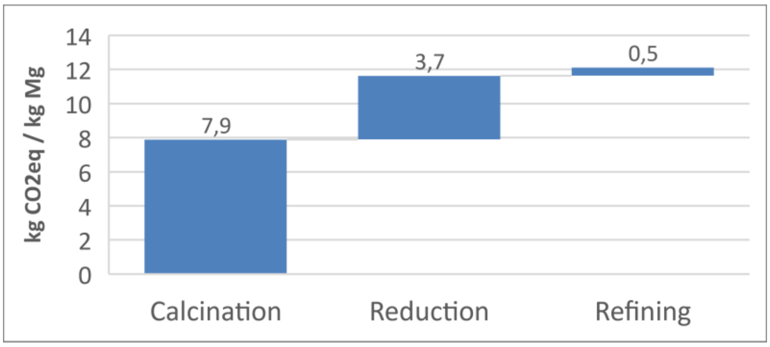

Figure 2: Weighted average greenhouse gas emissions per process and contribution to total emissions (only emissions of the Pidgeon process without upstream processes)[1]

Other Processes on Industrial Level

Apart from the Pidgeon process in China, there are some other plants which provide primary magnesium (Figure 3). Another plant using the Pidgeon process is located in Central Turkey. This plant has also a solar power unit. Its CO_{2eq} emissions are in a similar range to those of the Chinese Pidgeon process (Ehrenberger and Brost 2015). Considerable savings potential results from the possibility an alternative source of FeSi which uses a higher share of renewable electricity. Another plant located in Brazil uses a silicothermic process which is a modified type of Bolzano Process. (Russ, Sandilands, and Hasenberg 2012) have calculated CO_{2eq} emissions of 10.1 kg per kg magnesium. This includes a credit for the CO_2 uptake by eucalyptus trees that are used as biomass in the production process.

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[1] No direct CO_2 emissions result from the briquetting process step.

Alternatively to thermal production pathways, primary magnesium can be produced via electrolysis. In this case, the emissions depend mainly on the energy source used for this process. The 2013 LCA study analyzed an electrolytic process located in Israel in detail (Ehrenberger, Dieringa, and Friedrich 2013). With credits for the process by-products, the global warming potential is 14.0 kg CO_{2eq} per kg magnesium. Another electrolysis plant is located in the province of Qinghai, China (Magontec 2017). In this process, pure magnesium is produced from magnesium chloride ($MgCl_2$) brine which is a waste product of the adjacent potash production. The energy for the plant stems from different sources. The overall greenhouse gas emissions of the electrolysis amount 8.5 kg CO_{2eq} per kg magnesium. Crediting the further use of chlorine as by-product of the process, the magnesium electrolysis leads to overall emissions of 5.3 kg CO_{2eq} per kg of magnesium.

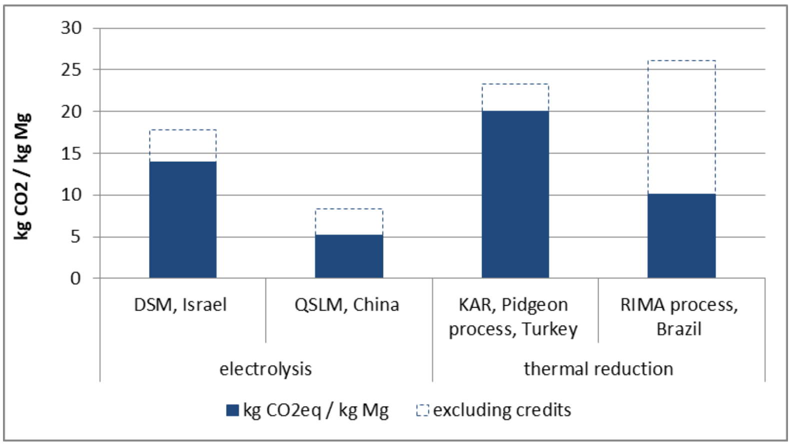

Figure 3: Greenhouse gas emissions of further industrialized magnesium production sites

Production Processes on Project Level

In the past years, there have been various projects for establishing new production processes for primary magnesium. Generating low environmental impact in magnesium production is one criterion for establishing new processes. This can either be achieved by using renewable energy, by avoiding pollutant emissions or by using waste of other industrial processes as raw material. Figure 4 shows the greenhouse gas emissions of two different processes. One is a hydrometallurgical process in Canada combined with an electrolytic process using serpentine as raw material. Combined with a low carbon energy supply, this results in greenhouse gas emissions lower than 5 kg CO_{2eq} per kg magnesium (Fournier 2017). Another planned primary magnesium production site in Australia uses fly ash, a waste material from another industrial process, as raw material. As a thermal process, the process as such has higher CO_{2eq} emissions compared to the electrolytic process. But the remaining ash waste generated from the process can be used as a cement substitute in the concrete industry. Credits given for the use of this by-product lower the emission balance to about 7.5 kg CO_{2eq} per kg magnesium (Paterson 2020).

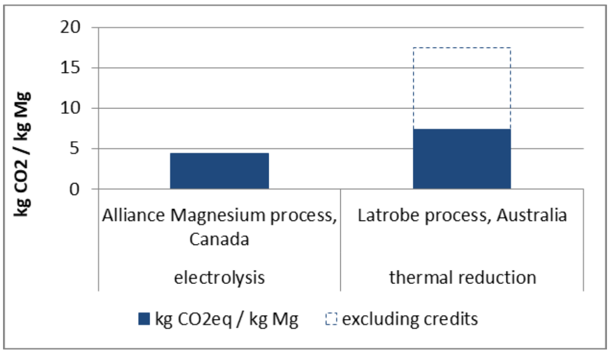

Figure 4: Greenhouse gas emissions of magnesium production on project level

3 Analysis of End of Life and Recycling

A detailed analysis of different magnesium recycling pathways can be found in the 2013 LCA report. The following information adds an analysis of secondary magnesium production in Europe to the data given in the original report. Furthermore, results of the IMA study "Magnesium Recycling in the EU" (Bell et al. 2017) are presented and included in the analysis of the magnesium overall life cycle.

Recovery of Magnesium as secondary Alloy

During the manufacturing of magnesium parts or during the further processing, magnesium scrap is generated which in some sites is treated in-house, but often is delivered to dedicated magnesium recycling plants. Two plants run by Magontec GmbH in Europe are analysed. The resulting greenhouse gas emissions are quite similar for both sites (Figure 6). The energy supply is the dominant process for the recycling plant. Apart from the emissions of the process itself, the emissions of material transport have to be added to the GHG balance of the secondary magnesium.

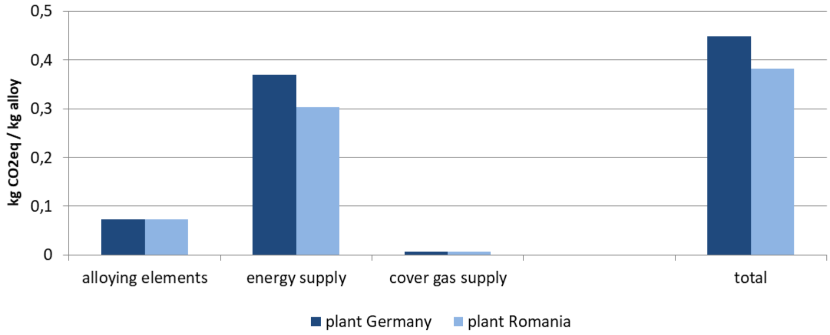

Figure 5: Greenhouse gas emissions from the recycling of new magnesium scrap

Recycling of End-of-Life Scrap

Technically, it would be possible to separate magnesium from the rest of the vehicle, but due to relatively low volumes per unit which reduce the economic benefits of recovering the magnesium less magnesium is recycled than possible. Bell et al. (2017) analyzed the fate of magnesium for automotive end-of-life parts. The figures are based on an analysis of statistical data on magnesium content in passenger cars, calculations of in-use accumulation and end-of-life vehicle statistics in Europe. Based on this analysis, we assume that functional and non-functional recycling of magnesium substitute for primary magnesium in the follow-up process for the analysis of the life cycle of the automotive part in this study. As presented in the 2013 LCA study, the contribution of vehicle's end-of-life processing is comparatively small (0.2 CO_{2eq} / kg recovered material), while the re-use of magnesium for aluminium alloying, as assumed as standard case in the 2013 LCA study, amounts to 3.6 kg CO_{2eq}.

4 Analysis of Magnesium Use

Magnesium as a Car Component

On average, magnesium shows higher emissions during component production compared to steel or aluminium on a per kg base. These higher emissions should be compensated during the use stage. The amount of fuel and emissions that can be saved depends on the weight savings. In this study, we compare a cross car beam (CCB) made of magnesium with the same part made of aluminium. The characteristics of the exemplary CCB are taken from Fackler and Berkmortel (2016). The main structure of the magnesium is cast out of magnesium. The magnesium part weights 4 kg and is made from an AM50 alloy. The weight of the aluminium part is 5.4 kg and an AlMg3 alloy is used. The emissions of the die casting process incl. alloying elements amount to 1.5 kg CO_{2eq} per kg material for the magnesium part and 1.4 kg CO_{2eq} per kg material in case of the aluminium part. The functional unit of the comparison is the use of the component in a passenger car with a life time mileage of 200,000 km. In case of aluminium we refer to a 90 % recovery rate, while magnesium has a recovery rate of 66 %.

For the ecological assessment of the use of lightweight materials in transport, the use phase has considerable influence on the overall balance. The calculation of the fuel savings using a fuel reduction value of 0.35 l gasoline per 100 kg and 100 km results in CO_{2eq} savings of 32 kg for the 200,000 km mileage. The component die-casting and the alloying elements account for 7.3 kg CO_{2eq} per component in case of magnesium and 9 kg CO_{2eq} in case of aluminium. The main contributor to the production emissions is the production of primary metal. Therefore, the emissions range considerably between the different sources of magnesium. Except for the low carbon QSLM production path, the production of magnesium has a positive difference to aluminium which means that the emissions for magnesium are higher in this life stage. This includes production of primary metals and alloys as well as the manufacturing of the CCB via die casting. The magnesium world average gives a hint on average emissions. Due to the dominance of the Chinese Pidgeon process, the value is similar to the average Pidgeon process. The emissions of the CCB production based on average Pidgeon process as source of primary magnesium amount to 115 kg CO_{2eq} while the emissions for the aluminium CCB assuming an average aluminium mix in Europe are 53 kg CO_{2eq}. The CO_2 emissions of the component using magnesium from the RIMA process result in a similar level like the aluminium reference.

For calculating the overall difference to the reference component, the emissions of the overall life cycle are summed up (Figure 6). The results show a positive net balance of greenhouse gas emission for all magnesium production scenarios that represent the current magnesium market. The results presented represent the range of current probable scenarios. They are valid for a comparison to the European aluminium use mix. If the aluminium part uses carbon intensive material produced in China, the result would look quite different. The same applies for scenarios where a share of low carbon secondary aluminium is assumed for the parts production. Equally, if other upcoming magnesium production paths are compared to the aluminium compontent, the magnesium components could gain much higher savings.

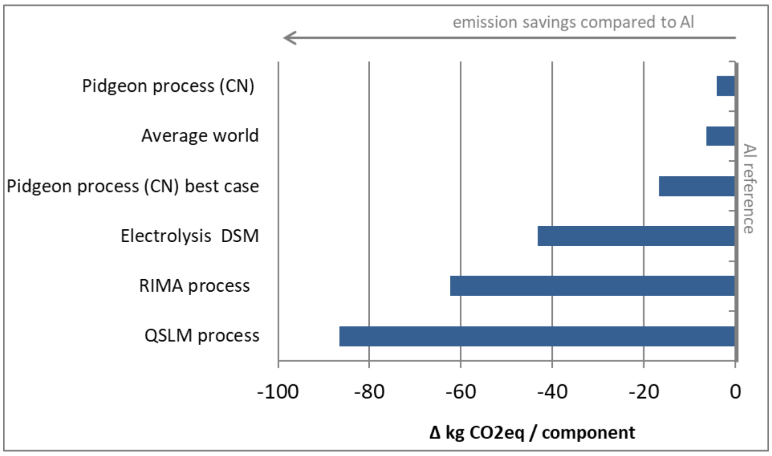

Figure 6: Overall greenhouse gas difference of different magnesium sourcing options compared to aluminium (used in Europe)

Aircraft Part

As the operation of aircrafts is energy intensive, the use of lightweight materials helps to reduce fuel consumption and emissions. To show the potential of emissions saving, parts used in an aircraft door are taken as an example. The parts are a gearbox and a seal closer for each of top and bottom of an aircraft door. The emissions of the sandcasting process incl. alloying elements amount to around 6 kg CO_{2eq} per kg material for the magnesium part and around 5 kg CO_{2eq} per kg material in case of the aluminium parts. The weight of the magnesium door parts amounts to 6.6 kg using an AZ91 alloy. The aluminium part (A356 alloy) which is used for component comparison weights 8.5 kg which is a weight difference of 22 %. The relation of aircraft weight and fuel consumption is taken from the DLR model VAMP zero. For the component example in this report, the fuel consumption is calculated for an A320. The correlation of fuel consumption and aircraft weight is analysed for a flight of 4,100 km and an operating empty aircraft mass of 41 t.

Only few flights are necessary to reach a break-even point for the amortization of higher emissions during component production. Due to the very high energy consumption of an aircraft during its flight, the absolute emission saving potential justifies the use of lightweight materials. Compared to the emissions of the use phase, the emissions of the magnesium pathways are almost equal to the aluminium reference. In any case, only a few mid-haul flights are necessary to compensate higher emissions of the use phase. In the examples shown in Figure 13, five or less flights are necessary for emissions compensation. If magnesium is produced via the RIMA or QSLM process, the production emissions are even lower compared the aluminium reference. Apart from the high annual mileage and greenhouse gas emissions, aircrafts have a long lifetime of up to 30 years which would lead to an even higher lifetime emission saving potential of almost 250 t CO_{2eq}.

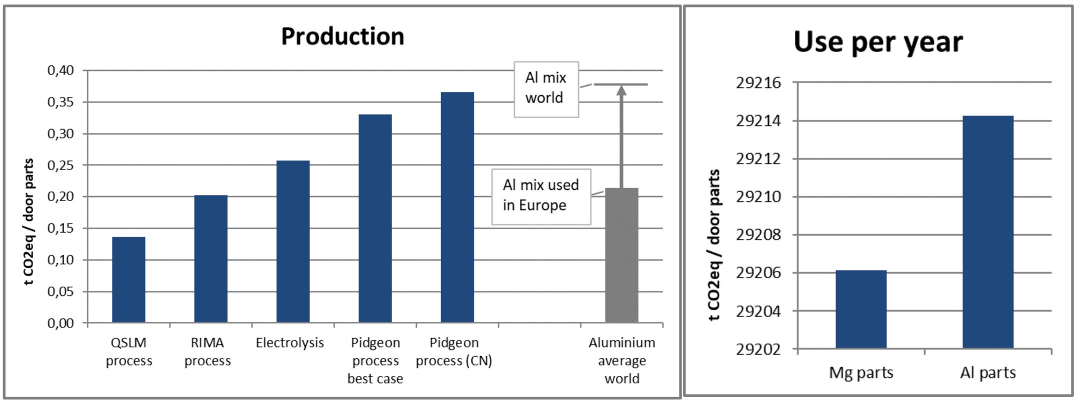

Figure 7: Greenhouse gas emissions from production of aircraft parts (left side) compared to annual GHG emissions during aircraft operation (right side)

5 Conclusions

Magnesium Production

- Emissions from magnesium production in the Pidgeon process have been reduced since 2011 (reference year of the 2013 LCA study). Yet, considering a potentially growing market for carbon neutral components in the car market, further improvements in magnesium production need to be achieved with a higher share of renewable energy. As the number of plants that have been surveyed for this study is limited, single plants can be below or above the figures presented in this study.
- Further reduction of the overall cradle-to-gate process emissions are possible, e.g. when using FeSi from alternative sourcing, though it is a question of further external factors whether this will happen or not. In future studies on magnesium production and application, the FeSi supply should be subject to further sensitivity analysis.
- The magnesium production site in Qinghai, China is a promising way to reduce the impacts from primary magnesium production. First calculations on the greenhouse gas emissions resulted in the lowest greenhouse gas emissions of all magnesium pathways that are currently in operation. The increased output of the Qinghai plant bears the potential of becoming a game changer for the world average magnesium. Other processes in Canada and Australia that are currently in planning stage show similar low CO_2 emissions and potential savings.

Magnesium Recycling

- The use of secondary material is a critical factor. Both aluminium and magnesium have established pathways for recycling and reusing scrap from parts production (post-industrial scrap) which is used for high quality secondary alloys. Though aluminium comes with an established end-of-life recycling loop, the actual content of secondary material that comes from end-of-life products into automotive components is less certain. Reuse of industrial scrap and of scrap from end-of-life vehicles are both important. Yet from a product's LCA perspective, recovery and reuse of materials from end-of-life vehicles is crucial.
- The share of end-of-life scrap of magnesium needs to be increased in the future. Though it would be technically feasible, a lack of established value-added chains for end-of-life magnesium scrap reduces the potentials of a functional recycling of magnesium parts.

Magnesium Use

- The use of magnesium in both transport application analysed in this report results in lower greenhouse gas emissions over the whole life cycle. The source of primary magnesium influences the point where higher emissions of the production phase are compensated. According to present literature (World Aluminium 2017, European Aluminium 2018), aluminium likewise shows a large range of emissions from primary production depending on its geographic source. The actual difference of emissions in such product comparison highly depends on the component characteristics and the material sourcing. Therefore, it is difficult to give generalized statements about the emission savings for these lightweight materials.
- The high fuel reduction potential for aircraft leads to extremely fast amortization of emissions from the production stage. The aviation industry should use more magnesium from this point of view.

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