Carbon Footprint of Magnesium Production and its Use in Transport Applications

Update of the IMA Report "Life Cycle Assessment of Magnesium Components in Vehicle Construction (2013)"

October 2020

DLR

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Preface

In 2013, the International Magnesium Association (IMA) published the study "Life Cycle Assessment (LCA) of Magnesium Components in Vehicle Construction" which has been written by the Institute of Vehicle Concepts of the German Aerospace Centre (DLR). The study analysed the entire life cycle of magnesium components for transport applications. This includes the production of primary magnesium, alloying, component production, use phase and the end-of-life of magnesium components. Focus of the study was the use of magnesium in passenger vehicles. Additionally, the life cycle of magnesium for the use as aircraft component was evaluated. Since the magnesium production and especially the Pidgeon process in China are subject of continuous improvements, an update of the LCA study reflecting the current production situation was necessary.

The update of the 2013 LCA study has been supported by various members of the IMA. In order to assure the quality of the study an advisory board has been set up. The members of the board are:

- Guy Adam (AMI)
- Martyn Alderman (Luxfer)
- Joel Fournier (AMI)
- Fernando França (Rima)
- Michael Just (Georg Fischer)
- David Klaumuenzer (Volkswagen)
- Dietmar Letzig (Helmholtzzentrum Geesthacht)
- Christoph Klein-Schmeink (Magontec)
- Martin Tauber (IMA)
- Jonathan Weiler (Meridien)
- Zishen Zhen (Magontec)

The members of the advisory board have supported the study with valuable information on magnesium production, manufacturing and recycling. We further thank the Chinese Magnesium Association for providing data of Chinese magnesium producers, David Paterson for providing information on the Latrobe process (see chapter 3.3) and Dr. Hajo Dieringa (HZG) for commenting this report.

The report includes a final evaluation by the external reviewer Christina Bocher (DEKRA).

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List of Abbreviations

CCB	Cross car beam
CMA	China Magnesium Association
CO_{2eq}	Carbon dioxide equivalents
COG	Coke oven gas
DSM	Dead sea magnesium
ELV	End-of-life vehicle(s)
FeSi	Ferrosilicon
GHG	Greenhouse gas(es)
IMA	International Magnesium Association
LCA	Life cycle assessment
LCI	Life cycle inventory
PG	Producer gas (equivalent to generator gas)
R134a	1,1,1,2-tetrafluoroethane (CH_2FCF_3)
SCOG	Semi coke oven gas
tkm	ton kilometer

1 Introduction

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. 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).

The worldwide primary magnesium market has been dominated by Chinese producers for the last twenty years. The share of magnesium from China is about 85% of the total primary production in 2019 and primary magnesium production in China amounted to more than 900 kt (USGS 2020). Until today, Chinese magnesium is mainly produced by thermal reduction with the so-called Pidgeon process. Other processes on the world market are thermal based processes in Brazil and Turkey as well as production sites for electrolysis in Israel, China and the US.

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:

- Being the most relevant magnesium production process, the focus is on the update of the data on the Pidgeon process (chapter 3.1). 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, which has a major influence on the cradle-to-gate emission balance, are updated.
- Additionally, information on the CO_2 balance of alternative existing and of newly planned magnesium production processes has been included in this analysis. In case of these processes, different data sources have been used (chapters 3.2 and 3.3).
- 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 has been included in this update (chapter 4).
- Finally, a new comparison of an automotive part with a reference part made of aluminum (chapter 5.2) and the analysis of the aircraft part of the 2013 study (chapter 5.3) is added

in this study in order to show the influence of the material production emissions on the entire life cycle of the product. These products serve as an example for showing how the magnesium source influences the results on greenhouse gas emissions.

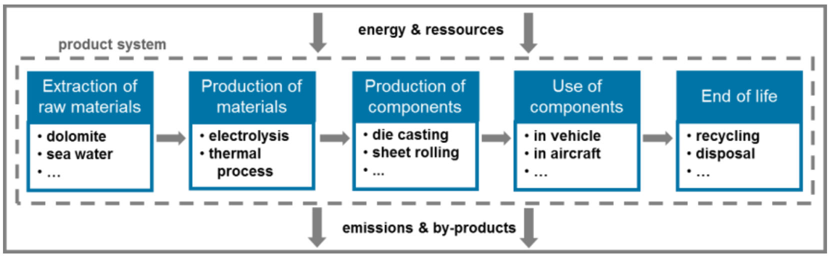

Figure 1: Overview of magnesium life cycle for transport applications analysed in the LCA study in 2013 (Ehrenberger, Dieringa, and Friedrich 2013)

2 Goal and Scope Definition

2.1 Goal of the Study

This study aims to assess the production of magnesium and its life cycle as lightweight material for the use in a passenger car and in an aircraft. 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) It focusses on the current situation of the Pidgeon process in China and on the analysis of other existing or emerging production pathways for magnesium worldwide. The 2013 study on "Life Cycle Assessment of Magnesium Components in Vehicle Construction" showed that the source of primary magnesium is the main driver for the overall environmental assessment of magnesium. In case of the Pidgeon process, more than 60 % of the overall greenhouse gas emission results from direct process emissions and energy supply. For the remaining 40 % of emissions by the use of raw materials, the main contribution is also from energy supply. Therefore, a special focus of this update is on the energy supply of the Pidgeon process. To complete the analysis of primary magnesium production, an overview of further production pathways is given. Additionally, new information on the recycling of magnesium has been added. This affects both the analysis of the magnesium recycling process as such which is fed with scrap from magnesium processing via various sources as well as the current situation of automotive end-of-life magnesium.

Based on this updated information and the data of the 2013 LCA report, the use of magnesium as material for a cross car beam (CCB) in a passenger car is assessed. The life cycle of the magnesium components is compared to the same part made from aluminum. As a second use case, the use of magnesium for an aircraft part is assessed. The models for all life cycle steps include all upstream processes which are needed to provide energy and material inputs for magnesium use.

The results of this study are available to all interested parties. The data on primary and secondary magnesium production are suitable for the use in other studies done by LCA practitioners. This data will also be available for different LCA databases. The aim of the parts comparison is to have valid examples for transport industry experts requiring information of the greenhouse gas balance of materials.

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 need 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.

2.2 General scope of the Study

General Aspects

The data used in this study represent the technological state-of-the-art. An attributional approach is used for the life cycle inventory modeling of this study. Depending on the process analyzed, data representativeness and quality varies. In general, for the core processes of magnesium production and end-of-life, primary data from various sources has been used. If not indicated differently, the data on the magnesium processing are taken from (Ehrenberger, Dieringa, and Friedrich 2013) and figures for upstream processes from the ecoinvent database 3.6 (ecoinvent Center 2019).

Input data and assumptions used for modeling the life cycle inventories have been reviewed by the advisory board of the study in order to ensure the use of best available data for every technology.

System Boundaries

The life cycle of magnesium production and of the magnesium component are analyzed separately. The analysis of the magnesium production is a cradle-to-gate assessment. All relevant upstream processes have been included for the calculation of the life cycle inventory.

Regarding the emissions into the environment, the models of magnesium production, processing and recycling are restricted to greenhouse gas emissions. There is no information included on other emissions. It is not expected that this restriction causes a relevant distortion of the results and conclusions, as emissions to air are the most important burden from the processes analyzed in this study.

Categories for Impact Assessment

For transport application, the reduction of CO_2 and other greenhouse gas emissions is one main goal. Lightweight design aims to reduce fuel consumption due to weight savings which would also reduce greenhouse gas emissions. Therefore, the impact assessment focusses on the impact on climate change which is expressed as greenhouse gas emissions or carbon dioxide equivalents (CO_{2eq}) for a time horizon of 100 years. The characterization factors for the greenhouse active emissions are taken from the Intergovernmental Panel on Climate Change (IPCC 2013).

Results for the impact categories acidification, eutrophication and resource depletion of magnesium production can be found in the original 2013 LCA study and are not subject of this update. Therefore, the use of the new data is limited to the analysis of greenhouse gas emissions and conclusions on other impact categories than climate change are not possible.

Documentation and Review

The data and models used in this study and its results are described in this report. As the study is intended for publication, the study is reviewed by an independent third party.

2.3 Scope of the Analysis of Primary Magnesium Production

Goal

For the magnesium primary production, the current Pidgeon process in China is evaluated and the status of alternative processes in China, Brazil, Turkey, Canada and Australia is presented. The basis of the analysis of the Pidgeon process is the 2013 LCA study. As the Pidgeon process is more energy intensive than other magnesium production processes and technology improvements target the energy efficiency, the use of energy for each process step is the focus of the current analysis. As more than 80 % is produced via the Chinese Pidgeon process, the results represent the majority of magnesium available on the global market. Like in the 2013 LCA study, the results are not supposed to be used for site specific analysis for Chinese magnesium, but for an average Pidgeon process located in China. Ferrosilicon production is not subject of this analysis, but an update of energy supply and a discussion on direct emissions has been included. Alternative processes are included in this study as far as data on the greenhouse gas balance is available. In case of these processes, different data sources have been used. The results on greenhouse gas emissions of the electrolysis in Qinghai, China and the Pidgeon process in Turkey stem from other DLR studies. Within the current study, the Chinese electrolysis data (Qinghai process) have only been updated using the current energy supply mix. All other process results (Rima, Latrobe, Alliance Magnesium) presented are based on information provided by the original magnesium producers. The data serve as guidance for the variance of the different processes.

Data collection and data quality

Similar to the 2013 LCA study, data on production statistics and fuel consumption have been gathered by the Chinese Magnesium Association (CMA). Data have been provided by magnesium producers. New data on energy consumption are provided with this update report. The current data survey revealed, that material consumption can be assumed to be similar to 2013. A hint on the potential benefits of using the production slag for other products is added. As there is no new data on the ferrosilicon (FeSi) production in China available, the data of the 2013 study is used apart from an update of energy, and especially electricity supply, as well as of direct CO_2 emissions of the process.

Data for other processes described in this report either on industrial or project level, are taken from company reports on greenhouse gas emissions.

System boundaries, background data and cut-offs

The product systems for magnesium production via Pidgeon process refers to a Chinese average data set. Main background data like electricity production, coal mining, dolomite mining and further background processes are based on the ecoinvent database 3.6. The Pidgeon process itself and the FeSi production as well as electricity, coal and producer gas production were modeled specifically for Chinese conditions within the 2013 LCA study. For upstream processes, where no Chinese data has been available, data on global or European average have been used from the ecoinvent database. The electrolysis analyzed in the 2013 LCA study is not affected by this update.

There are no general cut-off rules defined. The models for primary magnesium production include all material inputs for the production systems. Regarding the process outputs, the analysis is restricted to emissions into air. From FeSi production, only CO_2 and SiO_2 dust are included in the model as there is no information on other emissions available. In case of the Pidgeon process, the solid waste from the reduction furnace is included as output flow. This waste can possibly be sold for further use as filling material for road construction or similar applications.

Allocation and by-products

Allocations are equal to the 2013 LCA study. The ISO 14044 standard gives a preference to system expansion or dividing unit processes instead of allocation in case of multifunctional processes. As coke oven and semi coke oven gas are waste from (semi) coke production, the use of such productions wastes can be credited to the primary magnesium production. Magnesium producers use the gases either for free or at a low price. In order to show the influence on the allocation decision, the alternative method of giving credits for avoiding the waste of the coke oven and semi coke oven gas is presented as well as an allocation based on the energy content of the gases.

Functional unit and reference flow

The reference flow of both production systems is 1 kg of pure magnesium of the specific processes analyzed. Magnesium producers either sell pure magnesium or add alloying elements in the last step of production. Due to the variety of magnesium alloys, the assessment refers to the production of pure magnesium as functional unit. The alloy production is analyzed specifically in Chapter 4 of the 2013 LCA study.

Limitations

Within this study, only a limited number of 12 magnesium producing companies have been surveyed. The core upstream processes like electricity or coal supply are specifically developed for the region of China. Other upstream processes like sulfur production, are not available for this specific country in the ecoinvent database. Therefore, either global or European averages have been taken, depending on the availability. Due to the focus on greenhouse gas emissions, no conclusions on other environmental impact categories than global warming potential can be drawn.

2.4 Goal and Scope Definition for Magnesium End-of-Life

Goal

The aim of the 2013 study was to define a representative path of the end-of-life of magnesium parts in vehicles. We developed a model for the processing of end-of-life vehicles as well as for the reuse of magnesium. As a possible standard pathway we presented the further use of magnesium as an alloying element for aluminum. In this update, we correct the assumptions on recovery rates of end-of-life magnesium. The IMA study "Magnesium Recycling in the EU" which was published in 2017 presents current data on the fate of magnesium end-of-life parts (Bell et al. 2017). This information is used to update the analysis of end-of-life potentials of the used automotive parts. The vehicle end-of-life processes and possible processing as aluminum alloying elements are not affected by this update. Instead, we added a description of the magnesium recycling process for the production of secondary magnesium. Raw material can be either scrap from magnesium processing or end-of-life of magnesium products. This recycling process is company specific and represents two European plants run by Magontec GmbH. It is not intended to be used in another geographical context.

Data collection and data quality

The data on vehicle end-of-life treatment and reuse as alloying elements are taken from the 2013 LCA study. The figures on the production of secondary magnesium are based on data from one company and valid for 2020.

System boundaries, background data and cut-offs

The analysis of the magnesium end-of-life and of the production of secondary magnesium is a gate-to-gate approach. The production and use of the components is not included in the model. The data represents European conditions. No general cut-off rules are applied. In the case of the secondary magnesium production, the information on secondary aluminium and manganese is taken from the ecoinvent 3.6 database. As the LCA database does not provide information on beryllium supply, greenhouse gas emissions for beryllium production are taken from (Nuss and Eckelman 2014). For upstream processes like electricity production, data from the ecoinvent database v3.6 are used.

Allocation

As in the 2013 LCA study, the processes of the end-of-life vehicle treatment are allocated according to the mass of the component. In case of the secondary magnesium production, no allocation rules are needed apart from those applied in the ecoinvent v3.6 database.

Functional unit and reference flow

This part of the analysis is split into two separate processes. First, the recovery of magnesium as secondary alloy is calculated. The reference flow for this production of secondary magnesium alloy at the Magontec plants is 1 kg of secondary magnesium alloy. A second analysis is done on the vehicle end-of-life processes and the re-use of the magnesium vehicle parts as alloying element for an aluminium alloy (assumed as standard end-of-life recycling in the 2013 LCA study). The functional unit of the vehicle end-of-life model is 1 kg of secondary alloy which is available for reuse after passenger vehicle treatments and recycling. In the 2013 LCA study, the reference flow after the components end-of-life was assumed to be 1 kg of aluminum alloy (containing 3 % magnesium as alloying element; see chapter 5 in (Ehrenberger, Dieringa, and Friedrich 2013)).

Limitations

The analysis of secondary magnesium alloy production includes two plants of one company and is not applicable to other companies or geographic scopes. There is no average industry data available for these processes. The models for the vehicle end-of-life and material separation have not been updated in this study and represent the results of the 2013 LCA study.

2.5 Goal and Scope Definition of Magnesium Use in Transport Applications

Goal

Chapter 5 of this report covers the analysis of the overall life cycle of a vehicle and an aircraft component which are exemplarily analyzed in this study. The analysis aims to assess the potential advantages of the use of magnesium as material used for a cross car beam in passenger cars in comparison with aluminum. An additional comparison is made for the use of magnesium as aircraft door parts (gearbox and two seal closers).

Data collection and data quality

The calculation of the magnesium component example is based on the models for primary magnesium production, processing of magnesium and aluminum as well as end-of-life of magnesium and aluminum components as described in the 2013 LCA study and in this update report. The data on primary aluminum are taken from literature. For the calculation of fuel saving during vehicle operation, data on the dependence of fuel consumption on weight reduction is taken from literature. In case of the aircraft, the DLR model VAMPZero is used for determining the energy consumption of an exemplary flight.

System boundaries and background data

The calculations for the use of magnesium include the entire life cycle of the parts from cradle to grave for the cross car beam used in a passenger car and for the door part of an aircraft. As in the 2013 LCA study, “grave” refers to the end of the first life at which the used material is available for a second life.

Background data for fuel production are taken from the ecoinvent database 3.6.

Allocation

No allocation rules are needed apart from those applied in the ecoinvent v3.6 database.

Functional unit and reference flow

The use of the cross car beam in a gasoline passenger car for a driven distance of 200,000 km is the functional unit of this model. The calculation of fuel savings is based on the energy consumption of a gasoline passenger car.

The functional unit of the aircraft parts is the use of door parts in an aircraft on a flight of 4,100 km. The annual mileage of the aircraft is about 2 Mio. km and its lifetime is assumed to be up to 30 years.

Limitations

The results of the presented parts can only be seen as example, as various factors influence the overall emissions of the components' life cycle both in case of magnesium and aluminium. Due to the high range of emissions from primary metal production, the share of secondary metal content and recycling rates as well as the actual fuel reduction value for different drive trains, the absolute amount of emissions is case specific. Furthermore, only impact on global warming potential is considered and no conclusions on other environmental impact categories can be drawn.

3 Analysis of Primary Magnesium Production

3.1 Pidgeon Process in China

3.1.1 Process Steps

Today, Chinese magnesium is almost exclusively produced by thermal reduction using the Pidgeon process. Several process steps are needed from raw material preparation to the actual reduction process to magnesium (Figure 2). Raw material for the Pidgeon process is dolomite ($MgCO_3$•$CaCO_3$). During calcination, the dolomite is treated in continuous rotating furnaces at about 1,000 °C to 1,200 °C, in order to eliminate carbon dioxide (CO_2). In the briquetting step, the calcined material is ground and mixed with reaction agents. Main operating materials are ferrosilicon (FeSi) as reduction agent and calcium fluoride (CaF_2) as catalyst. Magnesium is then produced in the following chemical reaction in the reduction furnace:

$$2\,MgO \cdot CaO + Si(Fe) \rightarrow 2\,Mg + Ca_2SiO_4 + Fe$$

As the resulting raw magnesium still contains impurities, the material is refined with purifying agents. A detailed description of the Pidgeon process and its specifications can be found in the original LCA study (Ehrenberger, Dieringa, and Friedrich 2013).

As already described in the 2013 LCA study, one of the main improvements has been the substitution of coal by gaseous fuels in order to increase the energy efficiency of the process.

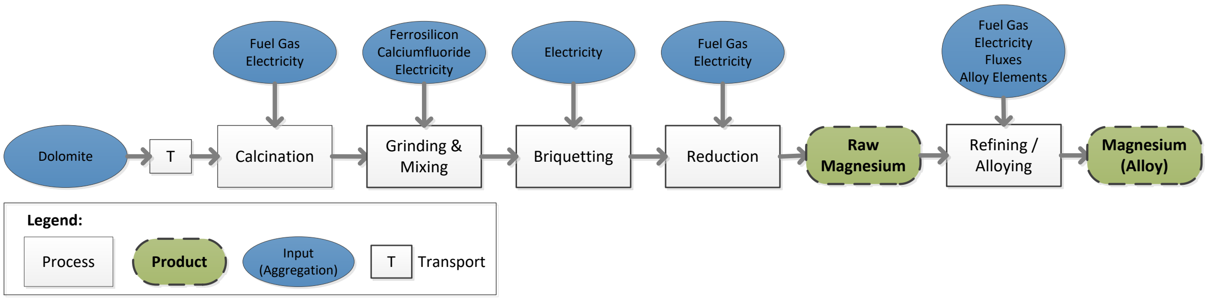

Figure 2: Overview of Pidgeon process steps and input flows (Ehrenberger, Dieringa, and Friedrich 2013)

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 is made in dedicated gas plants for magnesium smelters.
- Coke oven gas stems from a coking plant for e.g. iron blast furnace feed.
- Semi-coke oven gas stems from a semi-coke plant for ferro alloy feed. In contrast to coke oven gas, it is obtained at relatively low temperature (< 700 °C).
- Natural gas

3.1.2 Life Cycle Inventory for Pidgeon Process

The reference flow for the cradle-to-gate assessment of magnesium production in China is 1 kg magnesium ingot. Material and energy flows for the Pidgeon process are included in the analysis as well as the supply of operating and raw materials. For the calculation of the life cycle inventory we used the software tool Umberto LCA+. The data on the energy consumption of the Pidgeon process has been surveyed by CMA and represents the state of Pidgeon process in 2019. The production volumes and number of companies using the different fuels for running the process are shown in Table 1. Like in the prior LCA study, coal as an energy source is only used in for the calcination process. The use of the fuel gases is weighted according to the overall amount of magnesium which is produced with the respective gas per year. Compared to the data of the 2013 LCA study, a significant shift of production volumes can be observed. 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).

Table 1: Market share of companies according to fuel gas used

		Coke Oven Gas [m³/tMg]	Semi Coke Oven Gas [m³/tMg]	Producer Gas [m³/tMg]	Natural Gas [m³/tMg]
2019 Market Share	Number of companies	5	47	14	2
	Production Volume [t]	62500	619700	211300	75000
	Ratio	**6%**	**64%**	**22%**	**8%**

Table 2 shows the consumption of fuel gases for the single steps of the Pidgeon process. Like in the 2013 study, the data are averaged values from the production plants which have been examined. The average consumption of fuel gas as well as other production materials is calculated according to the number of companies without taking into account the individual production volume of the respective companies. For each fuel gas, a single scenario for the Pidgeon process has been calculated. The data for electricity consumption represent average consumptions for the companies which have been surveyed. A shift of electricity consumption between the single process steps can be observed. Electricity consumption mainly has decreased in the briquetting process step, while the use of further equipment for exhaust gas treatment increased the electricity need of other process steps. Therefore, the total amount of electricity used remains almost constant.

Other parameters like fuel gas composition and heating value, material consumption transport distances and melting yield remain equal to the 2013 LCA study. Detailed information on these parameters is presented in chapter 3 in (Ehrenberger, Dieringa, and Friedrich 2013). As the use of FeSi notably influences the overall balance, the upstream electricity sources have been updated according to the geographic distribution of FeSi producers.[1] As the electricity consumption of the FeSi production contributes considerably to the overall GHG emissions of the magnesium primary production, an alternative FeSi supply with a higher share of renewable energy would lead to a notable reduction of overall GHG emissions. As stated in the 2013 LCA report, direct 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 this figure in the 2013 LCA study was taken from measurement at Chinese ferro alloy production processes. Emissions of less than 1 kg CO_2 per kg FeSi have been reported which would require a correspondingly high share of CO emissions. The data vary considerably compared to other literature sources (Kero 2017; JRC 2017). Taken into consideration the material usage of the FeSi

[1] Information has been taken from "China ferrosilicon production analysis", November 2017, on https://www.cheegoole.com/2017-12-18-china-ferrosilicon-production-analysis/ (accessed June, 18, 2020).

process assumed in this study, direct emission of up to 4 kg CO_2/kg FeSi can be assumed which would be consistent with the data published by Kero (2017). This figure depends on the actual technical characteristics of the production process. One parameter is the coke consumption of the process which is assumed to amount to 0.9 kg per kg FeSi (Meng 2020) which is slightly lower than reported in Ehrenberger et al. (2013). Furthermore, current FeSi production in China largely takes place in regions with CO_2 intensive electricity supply. Yet some plants are located in regions with potentially less carbon 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).

Table 2: Overview of gas consumptions for production steps of Pidgeon process

		Coke Oven Gas [m³/tMg]	Semi Coke Oven Gas [m³/tMg]	Producer Gas [m³/tMg]	Natural Gas [m³/tMg]	Electricity [kWh/tMg]
Process Steps	Calcination	1300	5800	4820	1.4 t coal powder	300
	Briquetting					220
	Reduction	3000	6500	7760	1200	580
	Refining	500	950	800	110	130
Total		4800	13250	*14700*	*1500*	*1230*

3.1.3 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 results are shown for each step of the Pidgeon process and for the scenarios which reflect the use of four different fuel gases. For better transparency, the impact of the production of dolomite, FeSi and CaF_2 are shown separately.

The fuel gas and electricity consumption as well as transport are allocated to the single process steps. The production of FeSi, the calcination of dolomite and the reduction itself remain the most GHG-emission intensive life cycle steps (Figure 3). 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 for the scenarios natural gas, producer gas and coke oven gas. The data survey of the magnesium producers shows a certain variance in energy consumption. The analysis of the lower boundaries of energy consumption results in emission savings of about 2 kg CO_{2eq} per kg magnesium. Due to the reduced energy consumption, the emissions of the Pidgeon process are slightly 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 of up to 0.1 € / m³, 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 weighting considers the annual production volume of each of the scenarios as listed in Table 1.

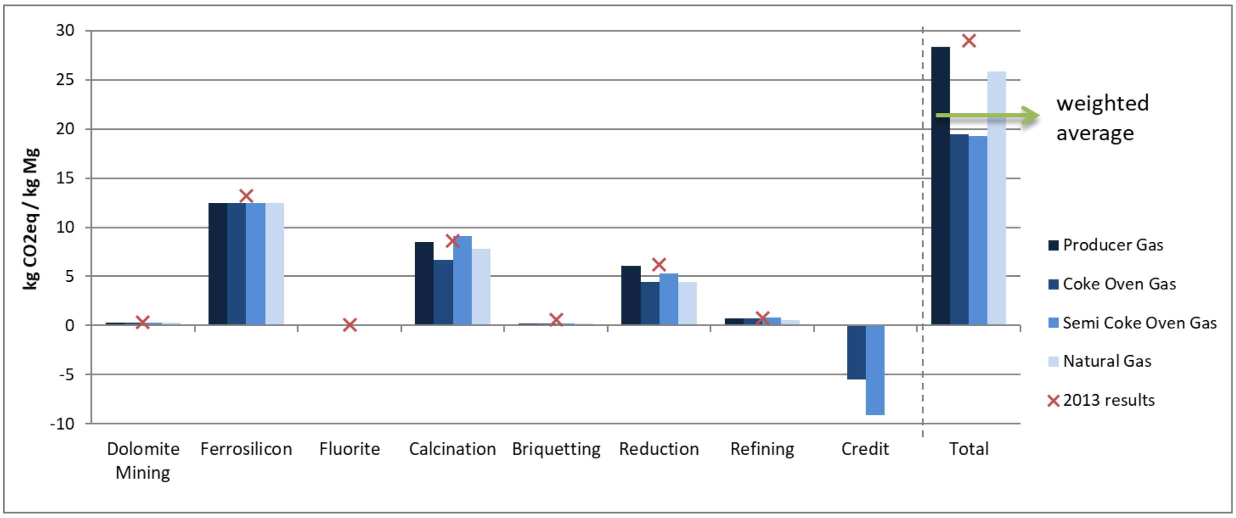

Figure 3: Greenhouse gas emissions of Pidgeon process[2]

The use of FeSi still is a major source of greenhouse gas emission in the overall cradle to gate assessment of the magnesium production and should be subject to further process improvements. Main contributing process steps of the Pidgeon process itself are calcination and reduction (Figure 4). The emissions of the Pidgeon process steps amount to 12.1 kg CO_{2eq} per kg of primary magnesium compared to 13.4 kg CO_2eq in 2011.

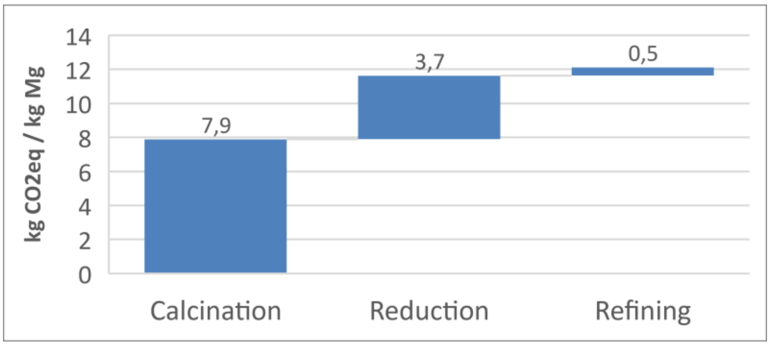

Figure 4: Weighted average greenhouse gas emissions per process and contribution to total emissions (only emissions of the Pidgeon process without upstream processes)[3]

[2] The 2013 results include a correction of the CO_2 emissions of FeSi production to ensure a better comparability to the updated values.

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

The solid waste materials from the reduction step of the Pidgeon process can be re-used for different purposes. The slag amounts to 5.6 kg / kg Mg. According to information of the Chinese Magnesium Association, about 50 % of the waste slag is reused, e.g. in cement production. Depending on the actual material that is replaced, emission savings of up to 0.1 kg CO_{2eq}/ kg material for the use in cement production can be saved via substitution. Assuming a 50 % rate of further used slag, this would amount to 0.3 kg of CO_{2eq} saved per kg Mg.

3.2 Other Processes on Industrial Level

Apart from the Pidgeon process in China, there are some other plants which provide primary magnesium (Figure 5). 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.

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). Its energy supply is based on natural gas. The raw material for this magnesium production in this case is carnallite ($MgCl_2$-$KCl \cdot 6H_2O$). Overall, the global warming potential of this process is 17.8 kg CO_{2eq}/ kg Mg when no credits for by-products are given. In this type of electrolysis plant, two by-products are produced: liquefied chlorine (Cl_2) and KCl-rich salt. The first has a wide range of potential uses and the second one can be converted to potassium fertilizer. 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 electricity supply of the magnesium production plant is mainly provided from water power (63 %). A smaller share of electricity is produced by photovoltaic cells in open ground installations 18%), by a cogeneration plant (12 %) and by wind power (8 %). The overall greenhouse gas emissions of the electrolysis amount 8.5 kg CO_{2eq} per kg magnesium. Apart from pure magnesium, the electrolysis of magnesium chloride produces gaseous chlorine. The amount of chlorine produced cannot finally be predicted as this state of the project, but a chlorine yield of around 2.5 kg per kg magnesium can be assumed. This by-product is used as feedstock for the nearby PVC plant. In order to credit the further use of the chlorine, the emissions which have been saved by not using chlorine from a conventional production have been calculated. Producing 2.5 kg of chlorine usually leads to greenhouse gas emissions of about 3.2 kg CO_{2eq}.

Thus, crediting these emissions which have been saved by the magnesium electrolysis leads to overall emissions of 5.3 kg CO_{2eq} per kg of magnesium ingot. The results presented are based on the assumption of full production volume. Yet, the Qinghai plant has currently not yet reached its full capacity, but is still in its ramp up phase. Therefore, the current greenhouse gas balance would presumably show higher emissions per kg of magnesium as a certain amount of energy is needed as basic load for the plant independently from the actual production volume.

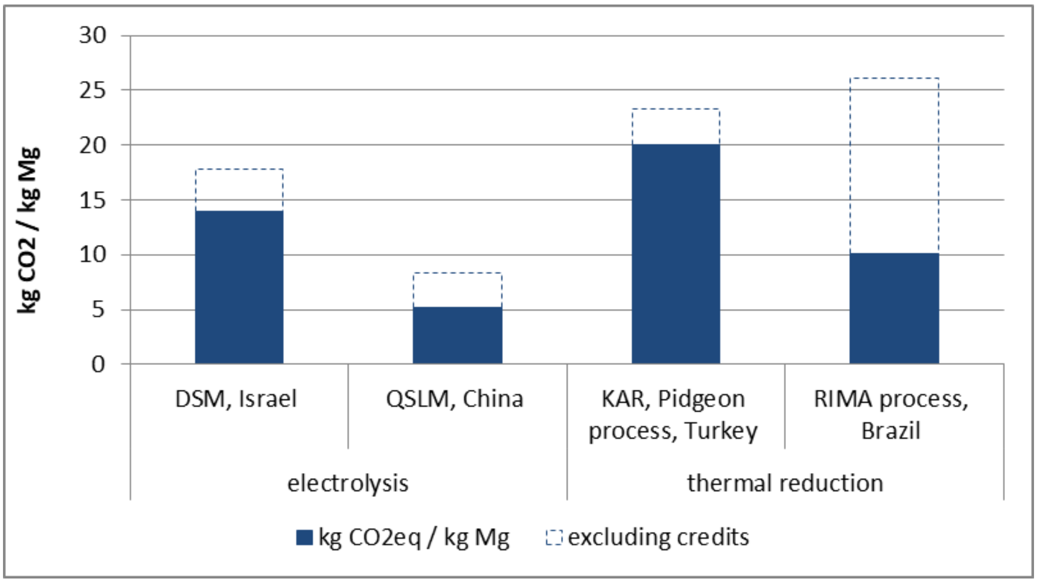

Figure 5: Greenhouse gas emissions of further industrialized magnesium production sites

3.3 Production Processes on Project Level

In the past years, there have been various projects for establishing new production processes for primary magnesium. Due to the nature of such project based processes, little information on the environmental performance is available. Nevertheless, 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 6 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 energy consumption is relatively high; 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).

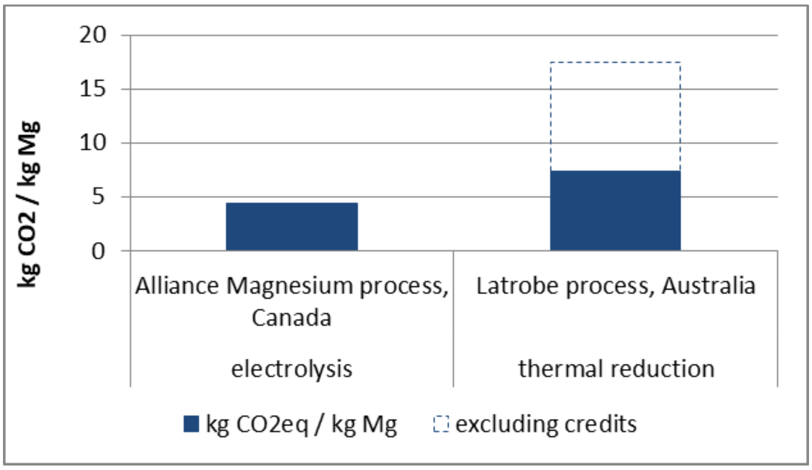

Figure 6: Greenhouse gas emissions of magnesium production on project level

4 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 in chapter 5.

4.1 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. In the following, two plants run by Magontec GmbH in Europe are analysed. For both plants, the processing of 1 kg of secondary alloy has been considered. The consumption of energy, cover gas and other raw materials are equal for both plants. The alloying elements that are typically fed into the process are aluminium, manganese and beryllium. The cover gas used in the recycling plants is sulphur dioxide (SO_2). Unlike fluorinated hydrocarbons, this compound has no effect on the climate, but has an impact on the potential acidification of natural resources. Though the electricity consumption is equal for both plants, the local electricity mix is different for each site. As both plants have no specific source of electricity, the national electricity mixes for Germany and Romania are used for the calculation of the greenhouse gas emissions. 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. Depending on the route and distance, this can have a notable share for the secondary material. Typical emissions of road and rail freight transport are about 90 g CO_2 per tkm for a EURO6 truck and 60 g CO_2 per tkm for an average train in Central Europe (ecoinvent 2020). If material is shipped over sea, a typical container ship emits about 10 g CO_2 per tkm (ecoinvent 2020).

It is important to note that the system boundaries of a product system and the origin of the scrap that is recovered play a major role in how the secondary magnesium is accounted in a greenhouse gas balance. If the secondary material is made from production scrap, it basically adds up to the production process of a product. If end-of-life scrap is added to a product, it can replace primary material. Therefore, the use of secondary material and the calculation of its environmental burden have to be carried out transparently.

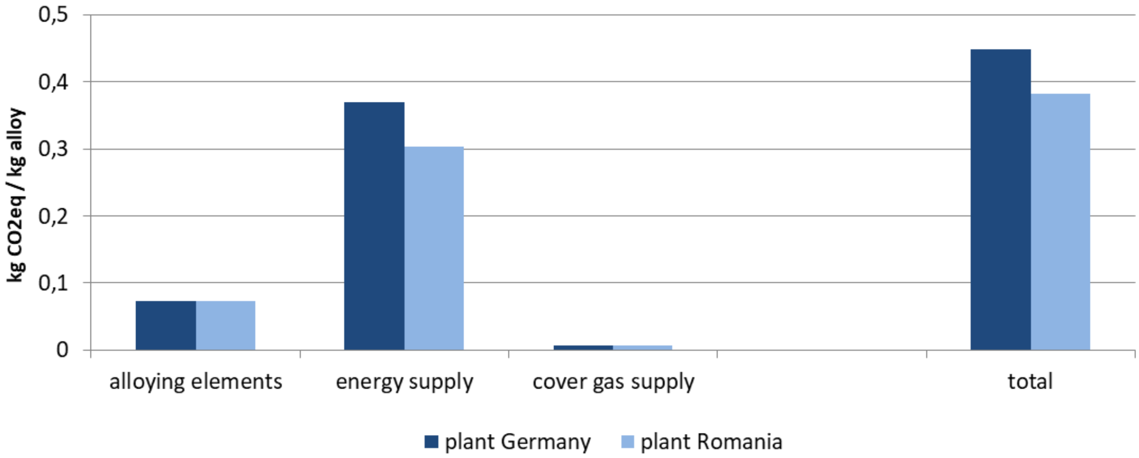

Figure 7: Greenhouse gas emissions from the recycling of new magnesium scrap

4.2 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 (Figure 8). 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. The authors estimate, that 18 % of vehicles treated at the end-of-life or exported from the EU in 2012 were in fact exported from the EU for reuse. They further assume that a considerable amount of non-ferrous scrap is still exported from Europe due to the attractive economics of hand sorting in low wage countries. The vehicles coming to end-of-life treatment facilities in Europe are depolluted and fluids are removed as required by the EU end-of-life vehicle directive. As already described in the 2013 LCA study, after shredding the vehicle body, the material is usually separated into a ferrous, non-ferrous and non-metallic shredded fraction. As standard process for the magnesium recycling, we assumed that 90 % of the magnesium ends up in the light-metal fraction as an alloying element for secondary aluminum production. Bell et al. (2017) further analyzed the end-of-life material flows and estimated that 20 % of the magnesium in end-of-life vehicles ends up in dismantled components and 80 % in the non-ferrous shredder fraction. On the one hand, dismantled material is more likely to be processed at re-melting plants. On the other hand, magnesium containing, but predominantly Al shredded material might be processed by refiners which remove magnesium in order to produce low magnesium casting alloys. Considering the available statistics and information in Europe, the authors conclude that 9 % of the available magnesium from end-of-life vehicles goes to functional recycling in aluminum scrap, 34 % is sent to disposal and 57 % ends up in non-functional recycling paths. For future magnesium recycling paths, the broader use of extruded profiles and sheet might change this picture, as they offer a better recyclability. Yet, this would require the implementation of efficient material separation and recovery processes.

For the analysis of the life cycle of the automotive part in Chapter 5 we assume that functional and non-functional recycling of magnesium substitute for primary magnesium in the follow-up process. 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}.

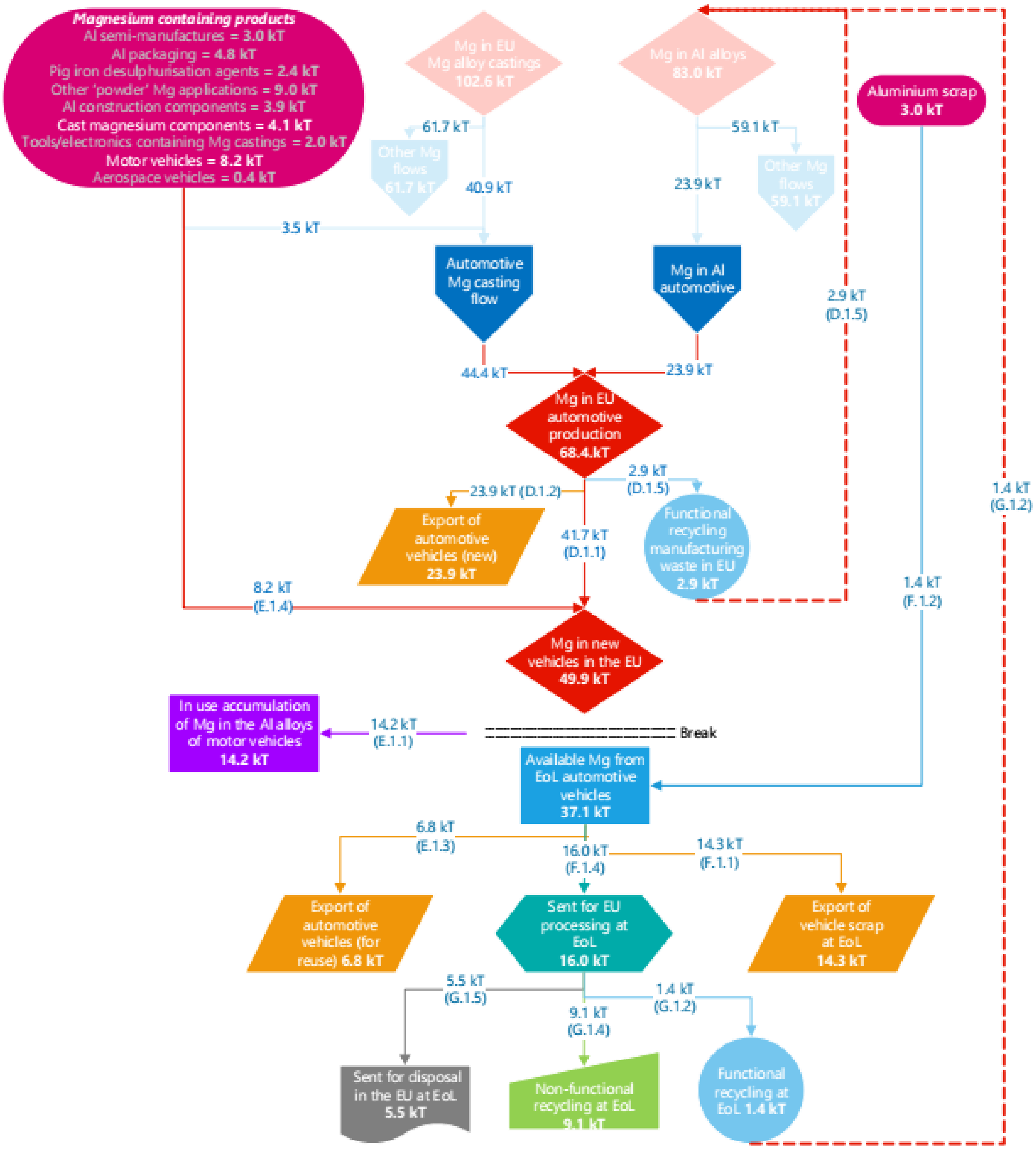

Figure 8: Map of downstream flows related to the magnesium use in automotive applications (Bell, Waugh, and Parker 2017)

5 Analysis of Magnesium Use

5.1 Comparison of Lightweight Materials

The calculation of emissions during material production is only one step in the assessment of materials for use in transport applications. Many lightweight materials have higher emissions in the production stage compared to steel. Figure 5 shows the greenhouse gas emissions (GHG) for different materials, including magnesium. But if we reduce the components weight due to the fact that we use magnesium instead of steel for the component with the same requirements and with the same technical functions this will reduce GHG emissions. As depicted in Figure 5, the range of potential emissions of most materials is considerable, and depends on the production paths, the geographic origin in combination with local energy supply, and material specifications.

For the material comparisons in chapters 5.2 and 5.3 we analyze part made via different magnesium pathways and compare the resulting greenhouse gas emissions to aluminum parts. As aluminum is produced in different part of the world with different energy sources for its production, the range of greenhouse gas emissions from different aluminum sources is considerably high (European Aluminium 2018; World Aluminium 2017). For the comparison in this report we refer to the aluminum mix that is used in Europe (in contrast to the European production mix) which has an average carbon footprint of 8.6 kg CO_{2eq} per kg aluminum (European Aluminium 2018).

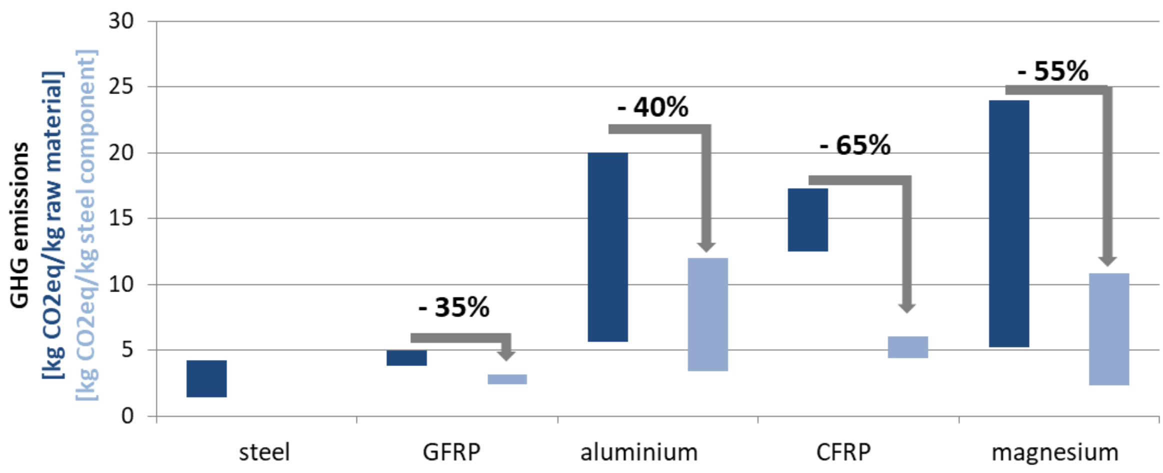

Figure 9: Greenhouse gas emissions of different metals and emission savings using the lightweight potential (GFRP: glass fiber reinforced polymer; CFRP: carbon fiber reinforced polymer; source: adapted from (Friedrich, Beeh, and Ehrenberger 2018); data source for GHG emissions: ecoinvent 3.6 database, own calculations)

5.2 Car Part

5.2.1 Methodological Approach

On average, magnesium shows higher emissions during component production compared to steel or aluminium on a per kg base (Figure 8). 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. Magnesium components can save about 25 % of weight compared to aluminium. In this case, the sources of primary metal as well as the end-of-life stage have a higher influence on the overall balance than in product comparisons to steel. 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. Additional small brackets can be made of magnesium, aluminium or steel. In this case study, we assume these brackets to be made 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 methodological approach of this product comparison follows the method applied in the 2013 LCA study. Also the main input parameters for the parts processing are taken from this 2013 LCA study (see chapter 4 "Analysis of Magnesium Parts Manufacturing in Ehrenberger, Dieringa, and Friedrich 2013). 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. Unlike in the 2013 LCA study the end-of-life recovery rates differ between both materials. In case of aluminium we refer to a 90 % recovery rate, while magnesium has a recovery rate of 66 % (see chapter 4.2).

One key parameter for the analysis of road vehicle components is the fuel reduction coefficient. The absolute value of this coefficient mainly depends on the type of drive-train and driving cycle. Alternative hybrid or electric vehicles provide less potential for energy savings from weight reduction due to the recuperation of energy during braking (Redelbach, Klötzke et al. 2012). Different approaches and absolute values for this coefficient can be found in literature. Koffler and Rohde-Brandenburger published figures on the fuel reduction potentials based on a generic modelling approach which provides data that is independent of the vehicle class and mass, engine size, or aerodynamic resistance of the vehicle (C. Koffler and Rohde-Brandenburger 2018; Rohde-Brandenburger and Koffler 2019; Christoph Koffler and Rohde-Brandenburger 2010). Kim and Wallington provide a statistical method of estimating mass-induced fuel consumption and fuel reduction values for specific models of passenger cars based on fuel economy and dynamometer test data available in the U.S. Environmental Protection Agency database (Kim and Wallington 2016). The resulting fuel reduction values are listed in Table 3. According to this analysis, the range of potential fuel savings is considerable and the choice of power train type for a specific analysis decides on the emissions saving of lightweight parts during the use phase. The fuel saving potential of vehicles driving electrically is one order of magnitude smaller than in case of conventional combustion engine vehicles. Yet, lightweight design is an important task also for electric vehicles, as it increases the electrical range of the vehicles. The calculations of this study do not consider absolute fuel consumption and emissions during vehicle use, but concentrate on saved environmental burdens due to the reduction of fuel consumption. The absolute fuel consumptions and related emissions of a car over a mileage of 200,000 km exceed the production or end-of-life contribution of the components by far. The relevant aspect for the comparison to two lightweight components is only the difference in emissions during the use stage.

Table 3: Fuel reduction values according to different literature sources and power-train types

	Rohde-Brandenburger (2010)		Kim (2016)	
[l /100kg*100km]	w/o PT adaption	with PT adaption	w/o PT adaption	with PT adaption
Gasoline	0.15	0.35	0.20	0.31
Gasoline -HEV	-	-	0.12	0.14
Diesel	0.12	0.27	-	-
PHEV - CS	-	-	0.12	0.14
PHEV - CD	-	-	0.056	0.056
BEV	-	-	0.050	0.050

5.2.2 Results for Greenhouse Gas Emissions

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. Figure 10 shows the greenhouse gas emission of the component production. 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. In this analysis, we focus on processes which provide magnesium on a large scale level. Other processes presented in chapter 3, like the electrolysis in Qinghai which is still in a ramp up phase, provide a significant potential of reducing the influence of the magnesium production (Figure 10). 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}.[4] The CO_2 emissions of the component using magnesium from the RIMA process result in a similar level like the aluminium reference.

[4] In this chapter, the terms "Pidgeon process (CN)" and "RIMA process" refer to the process results for greenhouse gas emissions including the relevant credits as described in chapter 3. "Pidgeon process best case" refers to the result for the Chinese Pidgeon process using coke oven gas (see Figure 3).

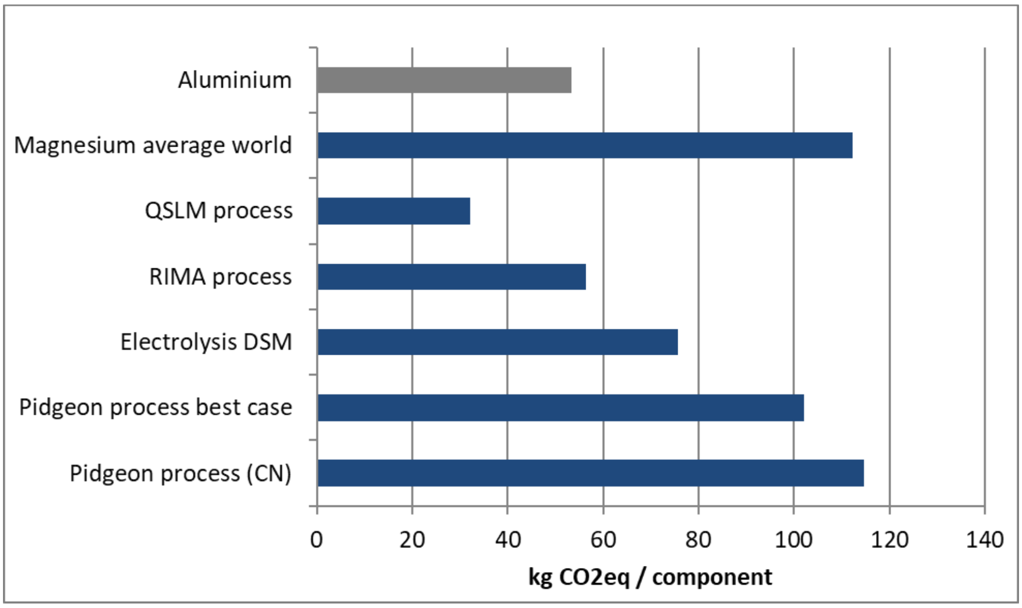

Figure 10: Greenhouse gas emissions of the cross car beam (CCB) production[5]

The differences in the single life cycle steps are depicted in Figure 11. Only the differences to the aluminium component are shown. 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 emission savings during the use stage are equal for all magnesium scenarios as they only depend on the weight savings. The recycling process amounts to emission saving of 11 kg CO_{2eq} for the magnesium component. Additionally, a credit for the substitution of primary material is included in the end-of-life calculation. This credit is based on the replacement of world average magnesium.

[5] World average magnesium refers to a production mix of 96% China, 2% Brazil, 2% Israel and 1% Turkey. The actual production mix is 85% China, 7.5% Russia, 2.4% Kazakhstan, 1.9% Israel, 1.4% Brazil, and the remaining amount provided by the rest of the world (with non-disclosed figures from US magnesium) (USGS 2020).

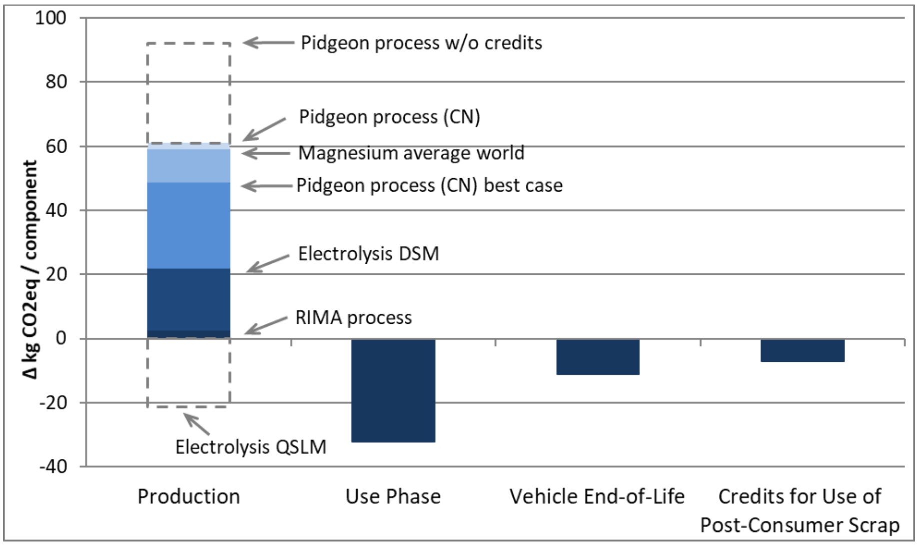

Figure 11: Difference of greenhouse gas emissions for different life cycle stages

For calculating the overall difference to the reference component, the emissions of the overall life cycle are summed up (Figure 12). The results show a positive net balance of greenhouse gas emission for those 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. As already stated in the 2013 LCA report, general conclusions on the comparison of magnesium and aluminium parts cannot be drawn without ambiguity.

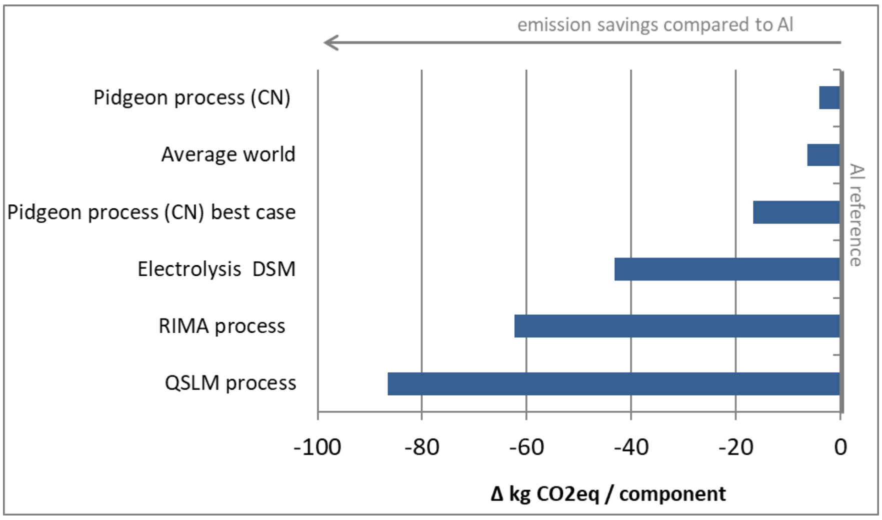

Figure 12: Overall greenhouse gas difference of different magnesium sourcing options compared to aluminium (used in Europe)

5.3 *Aircraft Part*

5.3.1 Methodological Approach

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 description of the production of the manufacturing of the magnesium and aluminium door parts via sand casting can be found in (Ehrenberger, Dieringa, and Friedrich 2013). 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. The definition of a reference flight distance is necessary as fuel consumption during take-off and landing is higher than during aircraft flight. The fuel savings are calculated for an aircraft where the weight is reduced (see Ehrenberger, Dieringa, and Friedrich 2013). We assume that the results of the model are also valid for small weight variations of an aircraft, as we only consider the lightweight potential of the door parts.

5.3.2 Results for Greenhouse Gas Emissions

As stated in the 2013 LCA study, 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}.

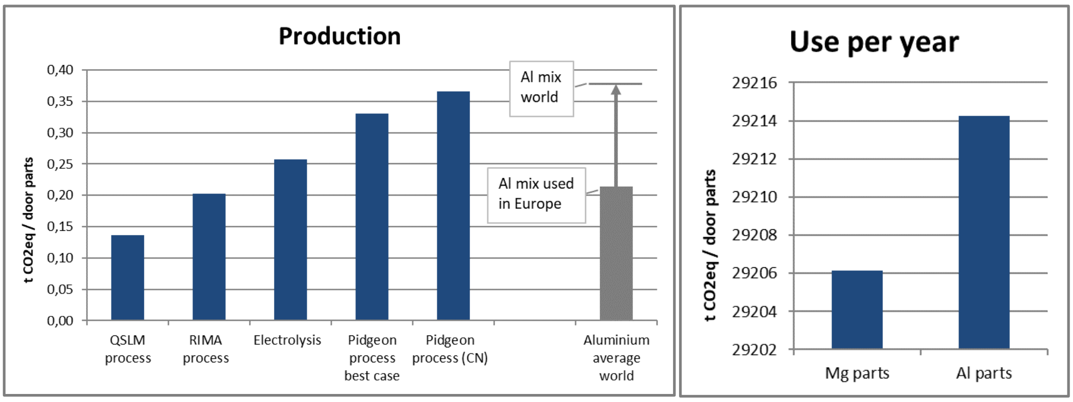

Figure 13: Greenhouse gas emissions from production of aircraft parts (left side) compared to annual GHG emissions during aircraft operation (right side)

6 Conclusions

Magnesium Production

- Emissions from magnesium production in the Pidgeon process have been reduced since 2011 (reference year of the 2013 LCA study), though the demand for low cost energy is somewhat contradicting a further reduction of emissions and no significant further technical improvement are expected in the near future. 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 and averaged values have been taken for the calculation of emissions, the results are also average data and 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, although it is still in its ramp-up phase. The electrolysis plant uses a high share of renewable energy for its electricity supply. First calculations on the greenhouse gas emissions resulted in the lowest greenhouse gas emissions of all magnesium pathways that are currently in operation. Reassessing the world average or Chinese emissions of magnesium production in the upcoming years is advisable, as the increased output of the Qinghai plant bears the potential of becoming a game changer. 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. Similarly, the presented results are only valid for the emissions of greenhouse gases. The analysis of other environmental impact categories might lead to different results.

- 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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Appendix

Although all Pidgeon process plants operate with the same process steps and the same principle in material conversion, energy consumption differs from plant to plant. This results from the energy efficiency of the equipment and from efficiency measures that are implemented. Additionally, the energy content of the different fuel gases varies which makes it difficult to directly compare the energy consumption of the processes. Table 4 lists the energy consumption of the single Pidgeon process steps converted into MJ per ton of magnesium (fuel gas + electric energy). This reveals a notable difference in the energy consumption of the processes between 2011 and 2019 as well as between the different pathways. The figures of the KAR plant in Turkey of 2014 are within the range of the other data, though its energy consumption is high compared to the natural gas plant data reported from China.

Table 4: Overview of energy consumption of different Pidgeon process variations

	[MJ/tMg]	Coke Oven Gas		Semi Coke Oven Gas		Producer / Generator Gas		Natural Gas		KAR plant
		2011	2019	2011	2019	2011	2019	2011	2019	2014
Production Steps	Calcination	43200	22324	47920	48299	26865	27023	36982	27811	48581
	Briquetting	2419	806	2419	806	2419	806	2419	806	1620
	Reduction	60012	51142	74439	55021	48647	43902	48774	46050	51287
	Refining	9985	8639	8318	8200	5708	4786	7501	4494	2880
	Total	*115616*	*82912*	*133096*	*112326*	*83640*	*76518*	*95676*	*79161*	*104368*

EXTERNAL REVIEW REPORT

Carbon Footprint of Magnesium Production and its Use in Transport Applications

Critical Review Statement

DEKRA Assurance Services GmbH
Sustainability Advisory Services
09.11.2020

CONTENT

Commissioned by:	International Magnesium Association (IMA)
Prepared by:	Simone Ehrenberger German Aerospace Center e.V.
Reviewed by:	Christina Bocher DEKRA Assurance Services GmbH
References:	▪ ISO 14040 (2006): Environmental Management – Life Cycle Assessment – Principles and Framework ▪ ISO 14044 (2006): Environmental Management – Life Cycle Assessment – Requirements and Guidelines

CRITICAL REVIEW STATEMENT

Scope of the Critical Review

The reviewer was tasked with assessing whether:

- the methods used to carry out the Life Cycle Assessment (LCA) are consistent with the relevant International Standards (ISO 14040 and ISO 14044),
- the methods and inventory modelling used to carry out the LCA are scientifically and technically valid,
- the data and model results used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The critical review was performed after the Carbon Footprint (CF) study was completed according to paragraph 6.2 of ISO 14044. This review statement is only valid for the specific report in its final version dated 30.10.2020.

The verification of the LCI model and individual background datasets is outside the scope of this review.

Review process

The review process was coordinated between the German Aerospace Center (DLR) and the reviewer. A first draft of the final CF report was submitted on 30.07.2020. The reviewer provided detailed comments of a general, technical and editorial nature to DLR. The comments were discussed during a review meeting on 27.08.2020.

During the review meeting, the reviewer also obtained detailed insights into the data collection of the current and the preceding study, the background datasets used from the ecoinvent database as well as the underlying software model in Umberto LCA+.

Another detailed web-conference took place on 28.09.2020 in which key comments and questions were discussed between DLR and the reviewer. All review questions and comments were clarified during this review meeting and therefore the model did not reveal any perceivable errors or shortcomings.

A final draft version of the CF report was provided to the reviewer on 29.09.2020. The reviewer checked the implementation of the comments and agreed to conclude the critical review process. The reviewer acknowledges the unrestricted access to all requested information, the dedicated efforts of DLR to address the comments provided, as well as the open and constructive dialogue during the critical review process. The review excluded an assessment of the LCI model and selected datasets. The draft review statement was submitted on 22.10.2020. Based on the final version of the CF report, dated 30.10.2020 which contained editorial changes, the updated final review statement was submitted on 09.11.2020.

All versions of the documentation (reports and data), including the individual reviewer comments, questions and associated answers, are archived and can be made available upon request.

General evaluation

The study assesses the carbon footprint associated with the production of primary magnesium (cradle-to-gate), providing up-to-date global average GHG emission data.

The study was performed in a professional manner using state-of-the-art methods in conformity with ISO 14040 (2006) and ISO 14044 (2006).

The CF study is an update of the 2013 LCA study, now analysing greenhouse gas emissions only. It has been updated to reflect the current state-of-the-art magnesium production processes, which is dominated by the Chinese Pidgeon process. Therefore the average Chinese Pidgeon process is the key output of this update and the key focus of this critical review.

In addition, two more product systems are analysed, providing further insight but being not the major scope of this study:

1) End-of-life of magnesium components used in vehicles (company-specific gate-to-gate data set with limited applicability);
2) Use of magnesium in transport applications (examples for automotive and aviation compared with aluminium applications, cradle-to-grave with limited applicability).

The goals, reasons for conducting the study and the intended audience and application of the study are clearly described. The scope description provides adequate information on the product system to be investigated, the functional unit, the system boundary, data quality, cut-offs, assumptions and limitations, allocation procedures as well as the definition of the impact category global warming potential.

One essential aspect in this CF study is the modelling of the Pidgeon process. The contribution analysis reveals that in particular the FeSi production (upstream process), the calcination of dolomite and the reduction itself contribute substantially to the total CF. A deeper analysis shows that it is the electricity consumption and the fuel gas which derives this share of the GHG emissions.

The primary data and background data used, as well as the data quality are transparently described in the report. The main processes involved in the magnesium production can be considered high to very high. The calculation of the overall results are made in MS-Excel based on the LCIA results.

Despite all necessary due diligence performed during the critical review process by the reviewers, the commissioner of this CF study remains liable for the underlying information and data.

The CF study results are clearly presented in various meaningful diagrams and tables. In Addition, the results are interpreted with regards to dominant life cycle stages and most significant processes or materials contributing to the total carbon footprint.

Furthermore the study provides an overview of the various drivers and potential improvement options, as well as an indication for future updates in case of technology changes. The study results are further analysed and compared with values from other DLR-studies and literature for various processes. This provides interesting insights and gives guidance on the variance of the various processes that exist or that are being developed. Since this is only of informative nature, this additional information was not part of the critical review.

As with every CF, the outcomes of a specific study also depend on the choices made in the scope definition. Therefore, the results need to be interpreted in the context defined. It should be noted that the outcomes of the study may not be generalised beyond the defined scope.

Conclusion

Overall, this LCA study can be considered very detailed and robust. The study has been carried out in conformity with ISO 14040 and ISO 14044. The reviewer found the methodology and its execution to be adequate for the defined purposes of the study. Furthermore, underlying data, the life cycle model, assumptions and calculations are appropriate and valid and lead to plausible results. The interpretation reflects the results in a suitable manner and relevant conclusions and recommendations are drawn.

Stuttgart, 09.11.2020

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