



# Life Cycle Assessment of Magnesium Components in Vehicle Construction



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# Executive Summary

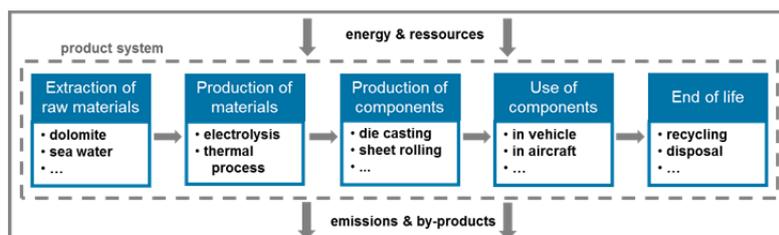
## 1 The IMA LCA Study

Magnesium has considerable potentials as lightweight material for many applications. It offers valuable advantages in transport. Looking for strategies to lower emissions from the transport sector, we find lightweight design to be one of the key solutions to increase the efficiency of road vehicles, trains or aircrafts. In order to evaluate ecological benefits from lightweight design and to prevent trade-offs between single life stages, potential advantages and disadvantages from such materials have to be weighted for the whole life cycle.

This executive summary presents the main results of the study “Life cycle Assessment (LCA) of Magnesium in Vehicle Construction” which has been initiated by the International Magnesium Association (IMA). The study analyses the entire life cycle of magnesium components for two exemplary transport applications. This includes the production of primary magnesium, alloying, component production, use phase and the end-of-life of magnesium components. For the use phase, examples for vehicle and aircraft components are selected to show benefits compared to aluminium. The results of the study provide up-to-date information about potentials concerning energy and emissions for the use of magnesium. Therefore the study aims to provide valuable information for producers, manufacturers and end-users to design and determine the magnesium process with reliable data. The overall results of the study can be found in a detailed report which includes data for the life cycle inventory as well as results of the impact assessment. The study follows the standards for life cycle assessment ISO 14040 and 14044. The report includes a critical review by an external reviewer (Dr. Hans-Jörg Althaus, Switzerland) with broad experience in LCA of metals and transport. The critical review report is part of the full report of this study and concludes that the study and its documentation comply with the ISO 14044 standard in all relevant matters.

## 2 Goal and Scope

The study is divided in four parts (Figure 6): magnesium production, production of two exemplary components, the use of these components in a gasoline passenger vehicle and a mid-haul aircraft and the end-of-life of vehicle components. The life cycle of the magnesium components is compared to the same parts made from aluminium. The models for all life cycle steps include all upstream processes which are needed to provide energy and material inputs for magnesium use. The study intends to provide up-to-date and reliable data and results on magnesium production, processing and the end-of-life of magnesium car components. In general, for the core processes of magnesium production, processing and end-of-life, primary data from various sources has been used. Figures for upstream processes and for data gaps are taken from literature and the ecoinvent database 2.2.



**Figure 1: Overview of magnesium life cycle for transport applications**

The four life cycle steps of magnesium are analyzed separately. The analysis of the magnesium production is a cradle-to-gate assessment. Assessing these two production routes with up-to-date data, we provide a representative and up-to-date evaluation of present magnesium production. The alloy and component production as well as the end-of-life stage are analyzed gate-to-gate. Two exemplary magnesium applications are analyzed: a steering wheel frame produced via die casting for the use in a passenger car and door parts made via sand casting for the use in an aircraft. The door parts are a gearbox and a seal closer for each of top and bottom of an aircraft door. Both examples represent components that are currently in use in automotive and aviation applications. The alloy production is assessed as separate process step, but in practice the alloys can be created directly at the magnesium production site as last process step of magnesium primary production. The calculation of the use stage of the components presented above is evaluated in terms of greenhouse gas emissions. The entire life cycle of the parts from cradle to grave is evaluated for the steering wheel used in a passenger car. The analysis of the aircraft parts focus on production and the break-even point for the comparison of magnesium and aluminium parts during aircraft operation. The evaluation of the end-of-life of magnesium parts in vehicles and the recycling aims to assess a representative recycling path for magnesium components in vehicles in a gate-to-gate approach. The further use of magnesium as alloying element for aluminium is analyzed as standard path for today's end-of-life of magnesium components. Additionally, we analyze the recovery of primary magnesium as an alternative path.

The impact assessment for magnesium production, processing and end-of-life includes four impact categories. For all impact categories, we use the CML 2001 method. Focus of this study and of the discussion of the results of the impact assessment is the global warming potential. For the impact assessment of greenhouse gas emissions (GHG), all emissions relevant for the greenhouse effect are calculated as kg carbon dioxide equivalents ( $\text{CO}_{2\text{eq}}$ ) for a time horizon of 100 years. The overall analysis of the components' life cycles and the comparison with aluminium is restricted to this category. Additionally, we calculate the results for the potentials of acidification ( $\text{SO}_{2\text{eq}}$ ) and eutrophication ( $\text{PO}_{4\text{eq}}$ ). The fourth category calculated in this study is depletion of abiotic resources ( $\text{kg Sb}_{\text{eq}}$ ).

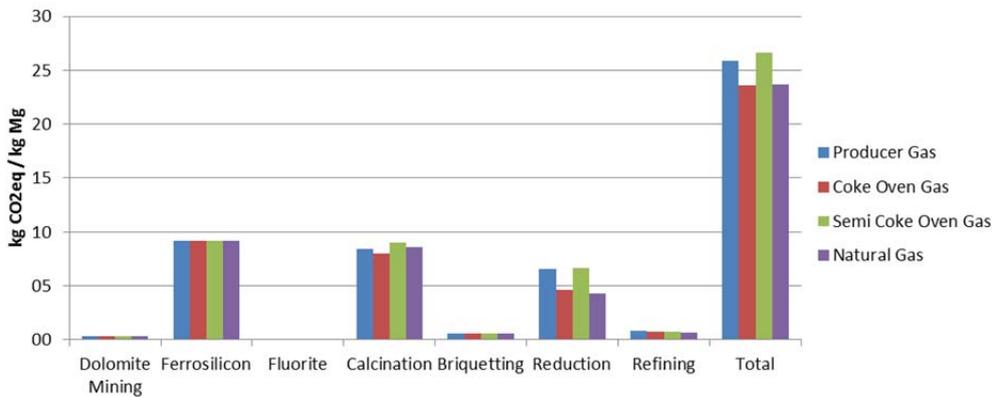
### 3 Analysis of Primary Magnesium Production

#### Pidgeon Process

For the magnesium primary production, recent technology developments and alternatives are evaluated. We develop a life cycle inventory for the production via Pidgeon process in China which represents the production in 2011. Coal as energy source is only used for the calcination process. For other process steps, coke oven, semi coke oven, producer or natural gas are used.

The plants running with natural gas use coal powder as energy carrier for the calcination process for economic reasons. For other gas fuels, the use of gas in the calcination furnace can be seen as standard in short-term, because there are no economic reasons for the use of coal. The impacts of this assumption as well as of a variation of other parameters, like gas composition, are subject to a sensitivity analysis. Figure 10 shows the greenhouse gas emissions of the Pidgeon process. The fuel gas and electricity consumption as well as transports are allocated to the single process steps. Clearly, the production of ferrosilicon ( $\text{FeSi}$ ), the calcination of dolomite and the reduction itself are the most GHG-emission intensive

life cycle steps. The weighted result for greenhouse gas emission of the Pidgeon process in 2011 is 25.8 kg CO<sub>2eq</sub> / kg Mg. The weighting considers the annual production volume of each of the scenarios. Regarding the contribution to the results for acidification, eutrophication and resource depletion, FeSi production is a dominant factor for all categories due to its high energy and material consumption.



**Figure 2: Greenhouse gas emissions of Pidgeon process according to fuel gas used**

The calculation of the standard scenario is based on an allocation for the production of coke oven gas and semi coke oven gas according to the energetic contribution of the fuel gases to the entire production from the (semi) coke plant. The emissions are completely accounted to the Pidgeon process. 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 production waste can be credited to the primary magnesium production. Thus, an alternative methodological approach is applied. By applying this approach, the weighted average GHG emissions of the Pidgeon process decreases to 19.9 kg CO<sub>2eq</sub> / kg Mg.

**Electrolysis**

In our study, we developed a model for an electrolysis which represents today’s conditions. The electrolysis model is site specific for the production of magnesium in Israel. Electrolysis plants in Russia are based on carnallite as well and most of the process steps and parameter are similar to the process evaluated in this study. In the carnallite based electrolysis plant, two by-products are produced: liquefied chlorine (Cl<sub>2</sub>) and KCl-rich salt. The first has a wide range of potential uses and the second one can be converted to potassium fertilizer. The production of these by-products is credited as it substitutes the production of the material from other routes.

For all impact categories, the electrolysis step itself is the dominant process followed by the preparation of the raw materials. Main factor for emissions and resource depletion is the consumption of electricity. For the global warming potential, the overall emissions amount to 17.8 kg CO<sub>2eq</sub> / kg Mg. The substitution of the production of the by-products in other processes can be credited in the impact assessment. In case of GWP the results decrease slightly to 14 kg CO<sub>2eq</sub> / kg Mg.

## 4 Analysis of Magnesium Parts Manufacturing

### Magnesium Steering Wheel (Die Casting)

The model for manufacturing a steering wheel which is used in a car refers to the steering wheel frame (referred as "steering wheel" in the following). The functional unit of the product systems is the production process of a magnesium steering wheel frame made from AM50 via die casting for the use in a passenger car. To prevent oxidation, the use of a cover gas is necessary. Three different alternative gas types are analyzed in this study: SF<sub>6</sub> / air mixture, SO<sub>2</sub> / air mixture and R134a / CO<sub>2</sub> mixture.

A further input parameter for the die casting process is the share of production scrap. Though data in literature appear to show that aluminium offers lower amounts of production scrap, this does not apply for the comparison of one product made from either magnesium or aluminium. For the evaluation of the production of the steering wheel, a standard scenario for die casting is defined. This scenario includes a rate of production waste of 45 %, the use of electric furnaces for die casting and the use of SO<sub>2</sub> as cover gas for the magnesium part. These parameters are seen as most representative for an exemplary steering wheel production. A second model for the production of a steering wheel made from aluminium has been developed.

The impact assessment of the die casting process shows that in general, the die casting step itself has higher environmental impacts than the further treatment of the parts. In both process steps, the magnesium steering wheel has lower impacts compared to the aluminium part. For the acidification category, the use of SO<sub>2</sub> as cover gas leads to comparatively high emissions. As the functional unit of the models is one steering wheel, the results include that for the magnesium component less material has to be processed. This implies also a lower energy consumption for the process.

### Magnesium Aircraft Parts (Sand Casting)

For the magnesium use in aviation, a gearbox and a seal closer for each of top and bottom of an aircraft door serve as example. The parts are produced via sand casting. The functional unit of the models developed for magnesium and aluminium is the production of all three parts together.

Unlike in the die casting process, the moulds have to be formed exclusively for the casting of each part. After the sand casting step itself, the parts have to be cut into shape and powder coated in a further treatment step. A second model for the production of sand casting parts from aluminium has been developed as well.

For the categories climate change and resource depletion, the production of magnesium parts has lower impacts than the production of aluminium parts. The potential impacts on eutrophication are in the same range. In the magnesium model, the production of the sand moulds has considerable influence in all impact categories. In case of the category climate change, the cast process itself is the dominant process due to the consumption of fluxes and energy. For the acidification potential, the use of SO<sub>2</sub> which is filled into the mould plays a major role for the magnesium parts.

## 5 Analysis of End of Life and Recycling

The processing of end-of-life vehicles consists of several steps. First, the vehicle is drained and specific parts are dismantled. The remaining car body is then shredded. The subsequent processes separate the materials from each other. Ferrous metals are removed by a magnetic separator. The remaining fractions are treated

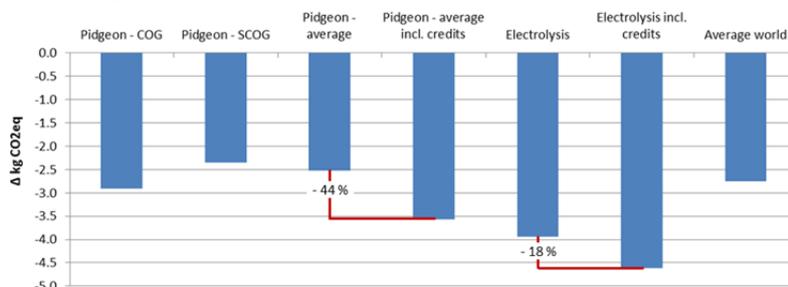
by different processes. The non-ferrous (NF) metals are composed of a mix of aluminium, magnesium and heavy metals (mainly copper). The NF-fraction can be separated in a float-sink plant or via x-ray separation, for instance. As for aluminium, recycling yields of 90 % are reported for automotive components, this rate is applied for the overall light metal fraction in this study. The recycling of magnesium within the aluminium cycle is seen as standard scenario for magnesium end-of-life.

As the energy consumption for the vehicle treatment is much lower than for the aluminium alloy processing, the impact of this process is significantly lower as well. For the global warming potential, the vehicle treatment contributes with 4 % to the overall emissions of 3.8 kg CO<sub>2eq</sub> / kg material. For other categories, the contribution ranges from 2 to 7 %.

## 6 Comparison of Magnesium and Aluminium Components

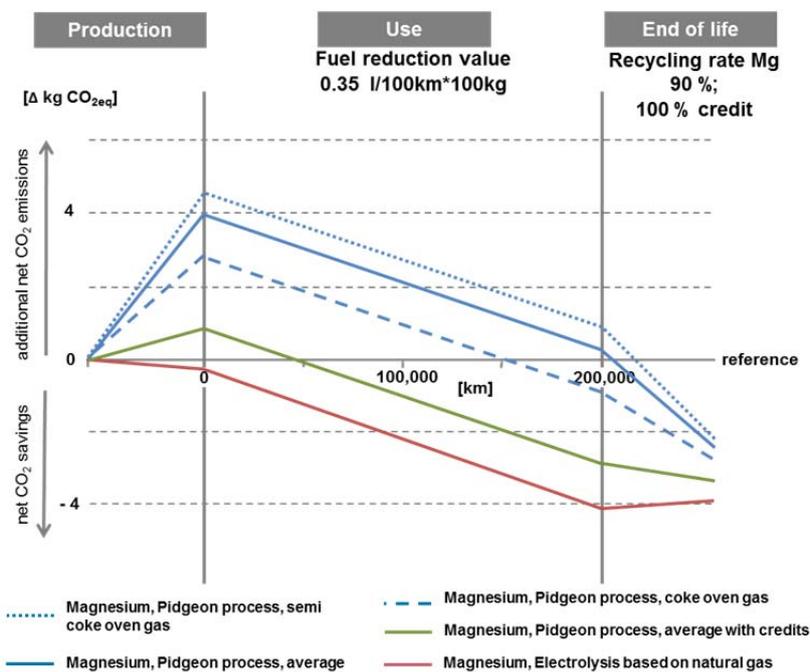
### Analysis of the Life Cycle of a Steering Wheel

For the ecological assessment of the use of lightweight materials in transport, the use phase has considerable influence on the overall balance. In the following, the results of the use stage calculations in the context of the overall life cycle balance of greenhouse gas emissions is presented for the component example “steering wheel” made from magnesium. The magnesium part is compared to a steering wheel made from aluminium. Only the differences of absolute emissions for component production, use stage and end-of-life are analyzed. Fuel savings are calculated for a middle class passenger car operated with gasoline for a mileage of 200,000 km. The fuel reduction coefficient is 0.35 l / 100kg\*100km. Figure 38 shows the overall balance for component production, use stage and end-of-life. The sum of emissions from production and end-of-life of the magnesium steering wheel are subtracted from the emission of the aluminium component. The results are calculated according to the source of primary magnesium. The average world scenario is based on a combination of GHG emissions from the average Pidgeon process and electrolysis. A share of 83 % Pidgeon process and 17 % electrolysis is assumed. The term “Pidgeon process – average with credits” refers to the Pidgeon process scenario for coke oven and semi coke oven gas in which these gases credited as waste gases. The recovery rates are assumed to be equal for both metals. For the aluminium reference, a world average is assumed as source of primary metal. The results show a positive net balance of CO<sub>2eq</sub> emissions for all magnesium production scenarios. The lowest advantage is reached when magnesium from the Pidgeon process based on semi-coke oven gas is used as primary metal. Magnesium from electrolysis leads to the highest savings of CO<sub>2eq</sub> emissions.



**Figure 3: Overall balance for magnesium steering wheel compared to aluminium steering wheel based on a mileage of 200,000 km**

Figure 40 reveals the break-even points for the main scenarios of magnesium production from Pidgeon process and electrolysis. Again only the differences of the absolute emissions from both material life cycles are depicted. The break-even point is reached at about 150,000 km for magnesium from a coke oven gas based Pidgeon process. The Pidgeon process using semi-coke oven gas as fuel does not lead to an amortization of emissions during the mileage of 200,000 km. As considerable amounts of magnesium are produced using semi-coke oven gas, the average Pidgeon process also shows a break-even point late in the life cycle of the steering wheel. When the use of coke oven and semi coke oven gas as production waste is credited, a break-even at 46,000 km is reached for the average Pidgeon process. In case of magnesium from electrolysis, the production of the steering wheel already results in lower emissions compared to the aluminium reference.



**Figure 4: Savings of greenhouse gas emissions during life cycle of a steering wheel for different magnesium scenarios**

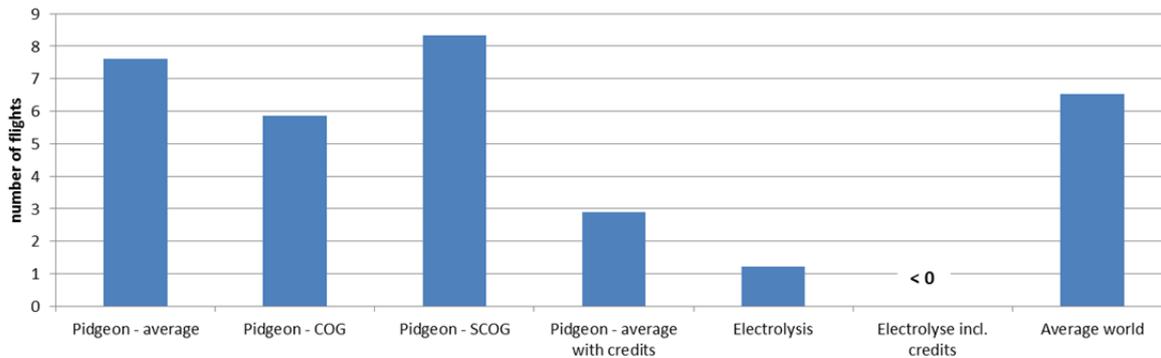
As the results for the comparison of GHG emissions are sensitive to both the source of primary metal and the vehicle and fuel consumption parameters of the use stage, general conclusions on the comparison of magnesium and aluminium parts cannot be drawn without ambiguity.

**Analysis of the Life Cycle of Components for Aircrafts**

The use of the aircraft parts is analyzed for application in an A320 aircraft. An exemplary use case representing a flight over a distance of 4,100km has been defined to calculate the emissions during aircraft operation. The relation of aircraft weight and fuel consumption is calculated using the DLR model VAMPzero. The end-of-life of aircraft components is not part of the study as it is not considered to be relevant for the greenhouse gas emissions of this use case.

In case of the comparison between aircraft parts of magnesium and aluminium, only few flights are necessary to reach a break-even point for the amortization of higher emissions during component production (Figure 44).

When magnesium is produced by electrolysis and the by-products are credited, the production of components has already fewer emissions compared to the aluminium reference. For other magnesium scenarios, the break-even point is reached at latest during the ninth flight. Due to high potentials of fuel savings during aircraft operation, the influence of component production and source of primary metal is insignificant.



**Figure 5: Number of flights for emission amortization for difference magnesium scenarios**

The maximum difference to the aluminum reference for component production is 0.18 t CO<sub>2eq</sub>. In contrast to that, the emission savings during aircraft operation amount to approximately 8 t CO<sub>2eq</sub> per year. Assuming a life time of 30 years for an aircraft, the reduction potential for magnesium components is about 226 t CO<sub>2eq</sub>. The following end-of-life of the aircraft does not notably influence the overall emission savings for the magnesium components.

## 7 Conclusions

- The magnesium production with Pidgeon process shows higher CO<sub>2</sub> emissions than magnesium from electrolysis. Due to improvements in the technical processes, the emissions have dropped significantly in the last few years.
- The recycling process does not contribute significantly to the overall emissions. To credit reuse of magnesium shows an important influence to LCA.
- The calculations on the break even points for the passenger car components are sensitive to the source of primary metal. The uncertainties from the vehicle specific parameters which lead to fuel and emission savings during vehicle operation are higher than the differences between the steering wheel alternatives.
- Already with existing magnesium-productions it is possible to gain advantages over aluminium if the magnesium-components are designed specifically to the magnesium-characteristics.
- In comparison with aluminium magnesium parts in aircrafts show significant benefits in terms of CO<sub>2</sub> emissions. In the use phase of the material high fuel reduction potential of magnesium parts for aircrafts leads to fast amortization of additional emissions from the earlier production stage.

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## List of Abbreviations

BJUT	Beijing University of Technology
CMA	China Magnesium Association
CML	<b>C</b> entrum voor <b>M</b> ilieuwetenschappen (Institute of Environmental Sciences) at University of <b>L</b> eiden
CO <sub>2eq</sub>	Carbon dioxide equivalents
COG	Coke oven gas
DSM	Dead sea magnesium
ELV	End-of-life vehicle(s)
FeSi	Ferrosilicon
GHG	Greenhouse gas(es)
LCI	Life cycle inventory
PG	Producer gas (equivalent to generator gas)
R134a	1,1,1,2-tetrafluoroethane (CH <sub>2</sub> FCF <sub>3</sub> )
SCOG	Semi coke oven gas
UCTE	Union for the Co-ordination of Transmission of Electricity

## Preface

This report presents the results of the study “Life cycle Assessment of Magnesium in Vehicle Construction” which has been initiated by the International Magnesium Association (IMA). The study analyses 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 is the use of magnesium in passenger vehicles. Additionally, the life cycle of magnesium for the use as aircraft component has been evaluated.

The study has been supported by various members of the IMA. In order to assure the quality of the study and to advice the project team where decisions on methodology, system boundaries and assumptions for process modelling had to be taken, an advisory board has been set up. The members of the board are:

- M. Alderman, Magnesium Elektron
- Dr. H. Dieringa, Helmholtz Centre Geesthacht
- F. França, RIMA
- Dr. C. Haberling, AUDI AG
- E. Lerer (until June 2012) and V. Kotlovsky (since June 2012), Dead Sea Magnesium
- M. Shukun, China Magnesium Association
- J. Willekens (until May 2012) and J. Westmann (May 2012 to November 2012), IMA
- Dr. Z. Zhen and Dr. M. Tauber (the latter since February 2012), Magontec

The members of the advisory board have supported the study with valuable data on magnesium production, manufacturing and recycling. Additionally, Dr. F. Gao (Centre of Materials Life Cycle Assessment, College of Materials Science and Engineering at Beijing University of Technology) and Prof. E. Aghion (Ben-Gurion University, Israel) supported this study by providing data on Chinese background processes and on current electrolysis. Furthermore, A. Koch, D. Böhnke and S. Langhans (Institute of Air Transportations Systems at DLR) provided data on fuel consumption and statistical data of aircrafts.

The Life Cycle Assessment Study (IMA LCA Study 2012) consists of four modules:

<b>Module 1</b>	<b>Primary magnesium production</b>
<b>Module 2</b>	<b>Advantages of magnesium-specific design and parts manufacturing</b>
<b>Module 3</b>	<b>Life cycle performance of magnesium in transport applications</b>
<b>Module 4</b>	<b>End-of-life and recycling</b>

The results of modules 1, 2 and 4 are described in part I of this report. Module 3 focuses on the analysis of greenhouse gas emissions during the use stage of the magnesium components' life cycle. Additionally, a comparison of the life cycle of components made from magnesium and aluminium is part of module 3. The results of module 3 can be found in part II of this report.

The report includes a final evaluation by an external reviewer (Dr. Hans-Jörg Althaus, Meilen, Switzerland) with broad experience in LCA of metals and transport.

# **PART I: Analysis of Primary Magnesium Production, Magnesium Processing and Recycling of Post-Consumer Scrap**

# 1 Introduction

Major global trends like scarcity of resources, climate change and increasing demand for mobility and transport also forces increasingly high efficient technical solutions. Specifications for CO<sub>2</sub> and / or fuel consumption in Europe and other parts of the world are severe and require significant improvements. Politicians, producers and market players ask more and more for reliable data on resource consumptions and emissions from materials used in transport applications, mainly in Europe and increasingly for example in China.

Light weight design is one of the actions to reduce energy consumption of all moving and accelerated parts in many applications.

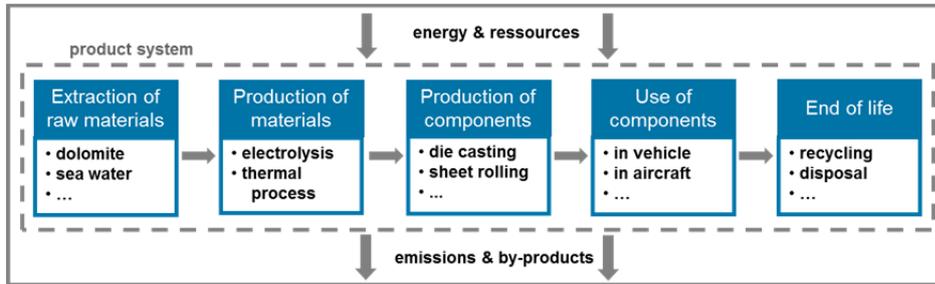
It is known that Sir Frederick Henry Royce (1863-1933) said: "Take the best that exists and make it better. When it does not exist, design it". If you apply this to the development of an optimum within the Multi-Material-Design-Strategy, magnesium can be highly successful because of its characteristics in production, manufacturing, use phase and end-of-life.

Magnesium has considerable potentials as lightweight material for many applications. It offers valuable advantages in transport. Looking for strategies to lower the emissions from the transport sector, we find lightweight design to be one of the key solutions to increase the efficiency of road vehicles, trains or aircrafts. In order to evaluate ecological benefits from lightweight design and to prevent trade-offs between single life stages, potential advantages and disadvantages from such materials have to be weighted for the whole life cycle of a vehicle, train or aircraft.

Though magnesium has been used in vehicles for decades, further developments are necessary to enhance its potential as material for a broad application in the transport sector. Energy consumption and emissions from magnesium production are higher than for steel and often aluminium. The amount of fuel and emission savings which can be achieved during the use stage depends on the weight reduction which is attained by the use of a lightweight material. For magnesium, weight savings of about 55 % can be achieved compared to conventional steel and about 25 % compared to aluminium.

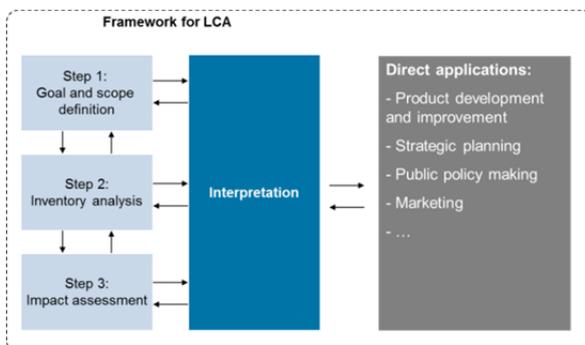
In order to assess the potential environmental benefits of magnesium, to show status and progress of different production routes to manufacture magnesium and magnesium alloys and to compare these with each other and with competitive lightweight materials (e.g. Al), the International Magnesium Association (IMA) initiated a study on the life cycle assessment of magnesium. Environmental concerns of the production and use of magnesium are addressed as well as the end-of-life of magnesium components. Hence the attractiveness of magnesium in the competition with other materials is shown for typical applications and demonstrated with real world data and calculated results for the needed energy consumption and respective emissions. A cradle-to-grave approach has been chosen in order to include all relevant effects during the life cycle of the material (Figure 6). For the use phase, examples for vehicle and aircraft components are selected to show benefits compared to aluminium. A magnesium steering wheel represents the use of magnesium in passenger cars and door parts made from magnesium are chosen as examples for aircraft components.

The results of the study will provide up-to-date information about circumstances and potentials concerning energy and emissions for the use of Mg. Therefore the study aims to provide valuable information for producers, manufacturers and end-users to design and determine the magnesium process with reliable data.



**Figure 6: Overview of magnesium life cycle for transport applications**

This study follows the standards for life cycle assessment DIN EN ISO 14040 and 14044 (ISO 14040 2006; ISO 14044 2006). The steps of an LCA as given in the standard are depicted in Figure 7. First step is goal and scope definition where the product system is defined. In case of vehicle components, a possible goal would be, for instance, the identification of the material which offers the lowest environmental burden over the entire life cycle of the component. This methodological framework of the study including the used impact categories is described in chapter 2. Next follows the calculation of an inventory of all material and energy flows of the product system. The inventories for the study on primary magnesium are described in chapter 3.1 for the magnesium production with Pidgeon process, in chapter 3.3 for magnesium production with electrolysis. The inventories for magnesium processing are found in chapter 4.4 for die casting and sand casting of the magnesium component examples and in chapter 5.4 for the end-of-life of magnesium. The material and energy flows of such inventories are then evaluated according to their impact on the environment. There are several categories for which such an impact assessment can be performed. The impact assessment results of magnesium production are described in chapter 3.4, for the production of magnesium components in chapter 4.5 and for the end-of-life of magnesium in chapter 5.5.



**Figure 7: Steps of a typical life cycle assessment (ISO 14040 2006)**

## 2 Goal and Scope Definition

### 2.1 Goal of the Study

The overall study aims to assess the life cycle of magnesium as lightweight material for transport applications. The study is divided in four parts: magnesium production, production of two exemplary components, the use of these components in a gasoline passenger vehicle and a mid-haul aircraft and the end-of-life of vehicle components. The life cycle of the magnesium components is compared to the same parts made from aluminium. 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.

This first part of the report addresses magnesium production, parts manufacturing and the end-of-life of automotive parts. The use of the component examples and an overall analysis of the whole life cycle in comparison to equal parts made from aluminium are presented in Part II. The specific goals of each life cycle steps analyzed in Part I are outlined in the respective chapters.

The study intends to provide up-to-date and reliable data and results on magnesium production, processing and the end-of-life of magnesium car components. Especially in magnesium production, major technical changes occurred in the past years both in the thermal process in China and in the electrolysis plant analyzed in this study. The results of the magnesium production evaluation can be used for any magnesium product as it is not part specific. The alloy making and manufacturing processes are specifically analyzed for a steering wheel and aircraft door parts, but the main influencing factors and general data on energy consumption and process materials are valid for other casting products as well. The results of the end-of-life analysis represent the typical process for passenger car components.

### 2.2 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, processing and end-of-life, primary data from various sources has been used. Figures for upstream processes and for data gaps are taken from literature and the ecoinvent database 2.2.

All input data and process parameters 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. Experts on magnesium production and processing as well as end-users are represented in the advisory board.

Detailed information on the scope of each life cycle step evaluated is presented in the respective chapters 3, 4 and 5.

## System Boundaries

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

Regarding the emission into the environment, the models of magnesium production, processing and recycling are restricted to emissions into air apart from upstream processes which have been taken from the ecoinvent data base. There is no information included on emissions to other environmental compartments. 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

The impact assessment for magnesium production, processing and end-of-life includes four impact categories. In general, the importance of each impact category in a LCA studies is mainly determined by the product system which is analyzed. For all impact categories, we use the CML 2001 method.

Focus of this study and of the discussion of the results of the impact assessment is the category global warming potential. For transport application, this is one main motivation. Lightweight design aims to reduce fuel consumption due to weight savings which would also reduce greenhouse gas emissions. This does not imply that other categories can be neglected. The results in this category generally have more impact on the comparison and evaluation of lightweight materials in the transport sector than other environmental categories. In order to show the main influencing factors in favor or against the use of magnesium from an environmental point of view in a straightforward way, we focus the analysis to the category "global warming potential". For the impact assessment of greenhouse gas emissions, all emissions relevant for the greenhouse effect are calculated as kg carbon dioxide equivalents ( $\text{CO}_{2\text{eq}}$ ) for a time horizon of 100 years. The characterization factors for greenhouse gases are based on models developed by the Intergovernmental Panel on Climate Change (IPCC).

Additionally, we calculate the results for the potentials of acidification and eutrophication, as the models include the emissions of  $\text{SO}_2$  and  $\text{NO}_x$ . The acidifying substances have various impacts on water bodies, groundwater, soil and organisms (also buildings are affected). The acidification potential is expressed as kg sulfur dioxide equivalents ( $\text{SO}_{2\text{eq}}$ ). The emissions of macronutrients to the environment can cause eutrophication when emissions are excessive. It is expressed as kg phosphate equivalents ( $\text{PO}_{4\text{eq}}$ ).

The fourth category calculated in this study is depletion of abiotic resources which is an input based category (not output based as the others). This category evaluates the extraction of minerals and fossil fuels which is needed for a product. The depletion factors are calculated

according to concentration of reserves and rate of de-accumulation. It is expressed as kg antimony equivalents per kg extraction ( $\text{kg Sb}_{\text{eq}}$ ).

For other impact categories, there is no information on potential emissions included in the primary data of the energy and material flow models. In case of the use of the hydroflourocarbon R134a as cover gas, the analysis of the ozone depletion potential (ODP) is not necessary as R134a has an ODP of zero.

### **Documentation and Review**

The data and models used in this study and its results are described in this report and in an executive summary. As the study compares different materials and the results are published, the study is reviewed by an independent third party.

## 3 Analysis of Primary Magnesium Production

### 3.1 Goal and Scope Definition for Magnesium Production

#### Goal

For the magnesium primary production, recent technology developments and alternatives are evaluated. We develop a life cycle inventory for the production via Pidgeon process in China which represents the production in 2011. As there have been considerable improvements in the Pidgeon process in the past years, we assess this process according to the combustion fuel used and show the influence of this energy source on the emissions based on average energy and material consumption data. We also calculate the emissions for the production of magnesium in an electrolysis plant based on carnallite as raw material. The electrolysis model is site specific for the production of magnesium in Israel. Electrolysis plants in Russia are based on carnallite as well and most of the process steps and parameter are similar to the process evaluated in this study. Assessing these two production routes with up-to-date data, we provide a representative and up-to-date evaluation of present magnesium production. As more than 80 % stems from Chinese Pidgeon process, the results represent the majority of magnesium available on the global market. But they are not supposed to be used for site specific analysis for Chinese magnesium. Regarding the model on electrolysis, the results are limited to the specific process based on carnallite which is analyzed in this study.

#### Data collection and data quality

For the Pidgeon process of the year 2011, data on production statistics and fuel consumption have been gathered by DLR and the Chinese Magnesium Association (CMA). Data have been provided by magnesium producers. The figures on material and energy consumption represent average data of Chinese producers. Regarding the composition of fuel gases, there is no average data available. Thus, the calculations in this study are based on measurements provided by CMA. The model for ferrosilicon (FeSi) production is based on data from 2008, as there has been no major change in production process or efficiency. The input data is based on data from three FeSi producers which have been interviewed by DLR in 2008. Data on energy consumption and direct emission from FeSi production are based on data collection from BJUT.

For the electrolysis process, data on energy consumption for the DSM plant from Aghion (2008) have been updated to the year 2011. Data on energy consumption have been provided by the magnesium industry (Aghion 2012; Kotlovsky 2013). For material consumption, data are taken from literature for the use of protection gas and from the data base ecoinvent 2.2 for other materials. The model on electrolysis represents a site specific electrolysis based on carnallite as raw material and does not reflect average magnesium electrolysis, as energy supply, cover gas utilization and the type and amount of by-products vary.

### **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 and coal mining are based on Chinese data from Chinese LCI database. Data on dolomite mining and further background processes are taken from the ecoinvent database v2.2. The Pidgeon process itself and the FeSi production as well as electricity, coal and producer gas production are modeled specifically for Chinese conditions. 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 process analyzed in this study is based on the production at DSM in Israel. For electricity and heat supply, data for the European UCTE net have been taken. The production of the cover gas is based on data from McCulloch and Lindley (2003) where the production of R134a is analysed for three sites in UK, USA and Japan.

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<sub>2</sub> and SiO<sub>2</sub> 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. Due to the lacking representativeness of this practice, the further use of the production waste is not analysed in this study.

In the electrolysis process, the consumption and direct emissions from the use of graphite anodes are not included, as consumption rate is very low and it is believed that only a part of the anodes wear-off can be directly translated into CO<sub>2</sub> emissions. Additionally, the off-gases run through scrubbers and the CO<sub>2</sub> is caught either by caustic soda or by calcium hydroxide. Due to the low relevance of these potential emissions and of the off-gas treatment compared to other process parameters, these flows are not considered in the electrolysis model.

### **Allocation and by-products**

Allocations are made for the production of coke oven and semi coke oven gas which are used as fuel gases for the Pidgeon process. The process for coke production is taken from the ecoinvent database and adjusted to Chinese conditions regarding electricity and coal production. Energy and material consumption for this process are allocated according to the energy content of the process outputs (coke, coke oven gas and tar). As there is no data available for semi coke production, the production has been assumed to be similar to coke production including assumptions on allocation. 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 for free, as coke producers are forced to find a customer for the waste gas. For semi-coke

gas, the situation is similar. As the status of these fuel gases is of economic nature and can change when the demand for these gases grows, the energetic allocation is set as standard case for the Pidgeon process. 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.

In case of the electrolysis process, there are two by-products: chlorine and potassium chloride. Both substitute the equivalent products from other production routes. This substitution is credited in an extra scenario for the electrolysis process.

### Functional unit and reference flow

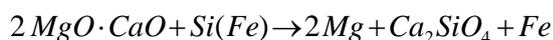
The reference flow of both production systems is 1 kg of pure magnesium. Magnesium producers either sell pure magnesium or add alloying elements in the last step of production. Due to the variety of magnesium alloys, the assessment refers to the production of pure magnesium as functional unit. The alloy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

## 3.2 Pidgeon Process

### 3.2.1 Process Steps

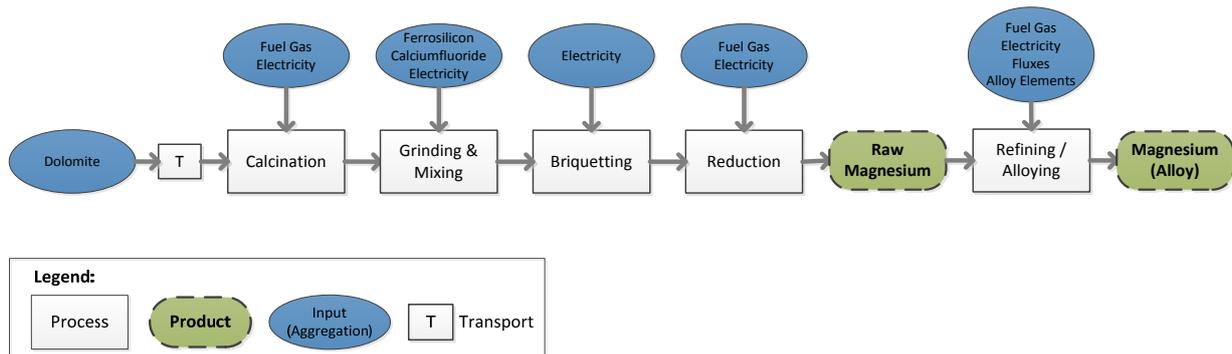
The worldwide primary magnesium market has been dominated by Chinese producers for the last ten years. The share of magnesium from China is about 80 % of the total primary magnesium production. In 2011, primary magnesium production in China amounted to 666,200 tons. Today, Chinese magnesium is exclusively produced by thermal reduction with the so called Pidgeon process. Figure 8 provides an overview of the single production steps which are needed to gain pure magnesium from its raw material.

Raw material for magnesium production in China is dolomite ( $MgCO_3 \cdot CaCO_3$ ). First step in the process chain is the mining and transportation of dolomite to the magnesium production site. 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 ( $CO_2$ ) from the crystal lattice. In the briquetting step, the calcined material is grounded and mixed with reaction agents. Main operating material is ferrosilicon (FeSi) which is needed as reduction agent. Additionally, calcium fluoride ( $CaF_2$ ) is consumed as catalyst. The reaction agents are pressed into briquettes and filled into reduction furnaces. Heating temperature for the reduction process is about 1,200 °C under vacuum. Magnesium is produced in the following chemical reaction:



The magnesium sublimates in the water cooled part of the furnace and is removed at the end of this batch process. The remaining parts of the input material (Fe,  $Ca_2SiO_4$  and other impurities) are part of the production slag which is either deposited or used as filling material in road

construction or similar applications. As magnesium crowns still contain certain impurities, the material needs to be refined with purifying agents. During refining, protection agents are needed to prevent the melted magnesium from burning as it is highly combustible. Chinese magnesium producers use sulphur or fluxes containing small amounts of sulphur for preventing the magnesium melt from burning. The use of sulphur dioxide (SO<sub>2</sub>) also takes place in some companies, but the use of sulphur powder is seen as representative case.



**Figure 8: Overview of Pidgeon process steps and input flows**

Former studies revealed that the Pidgeon process has received notable improvements concerning energy consumption and CO<sub>2eq</sub> emissions during the past years (see chapter 3.4.3). Most important subjects for enhancing the process efficiency have been the performance of reduction furnaces, the handling of retorts, and the reuse of waste heat and a further use of production waste. Furthermore, the type of energy source plays an important role for the environmental impact of the Pidgeon process. There have been major improvements by substituting coal by gaseous fuels due to a more efficient heating of furnaces and to a higher heating value of such fuels.

The fuel gases are defined as follows:

- Producer gas is made in dedicated gas plants for magnesium smelters. It is also known as coal gas or generator gas.
- Coke oven gas stems from a coking plant for e.g. iron blast furnace feed. Usually, the steel plant gives the gas to the magnesium smelter for free.
- Semi-coke oven gas stems from a coke plant for ferro alloy feed. The gas which would normally be released to atmosphere (after burning) is provided for free to the Mg operation. In contrast to coke oven gas, it is obtained at relatively low temperature (< 700 °C).

A major trend which can be observed is an overall process improvement by integrated production of several commodities. This means, that there is no need for material transports and the possibility of using by-products from one process as input for others. Concerning the Pidgeon

process, the installation of local production networks combining the production of coke or semi-coke with magnesium production offers some advantages. (Semi) coke oven gas which is a by-product from the (semi) coke production can be used as energy source for the Pidgeon process. The coke itself can also be used for FeSi production and long distance transports of raw materials can be saved in such local production networks.

### 3.2.2 Life Cycle Inventory for Pidgeon Process

For the cradle-to-gate assessment of magnesium production in China we assume an output of 1 kg magnesium ingot. We calculated the material and energy flows for the Pidgeon process as well as the supply of operating and raw materials using the software tool Umberto. The main process regarding the way of magnesium from mining to ingot casting consists of five steps as described above. Except from the mining of dolomite, the assessment of this study is based on primary data, in order to give a representative picture of the Pidgeon process.

The data on energy consumption have been surveyed by CMA and represent the state of Pidgeon process in 2011. Table 1 shows the number of companies using the different fuels used for the magnesium production. In 2011, coal as energy source is only used in for the calcination process. For other process steps, coke oven, semi coke oven, producer or natural gas are used. There are 74 magnesium production plants in 2011 of which 46 use semi coke oven gas as energy source. Second most used fuel gas is producer gas with 13 companies. Coke oven gas is used by 10 companies and natural gas by 5. As there is a considerable variance in annual magnesium output, the use of the fuel gases is weighted according to the overall amount of magnesium which is produced with the respective gas per year. From this point of view, semi coke oven gas still is the most important gas with a share of 45 %. 34 % of the Chinese raw magnesium is produced with producer gas as energy source. Only 14 % are produced with coke oven gas and 6 % with natural gas. For this study, CMA has surveyed 25 companies of which 7 use coke oven gas, 4 use semi coke oven gas, 11 use producer gas and 3 use natural gas.

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

	Coke Oven Gas	Semi Coke Oven Gas	Producer / Generator Gas	Natural Gas
<b>Number of companies</b>	10	46	13	5
<b>Magnesium production volume [t]</b>	95300	298400	229200	43300
<b>Ratio</b>	14%	45%	34%	6%

There is no exact information on the share of companies which still use coal in their calcination furnace. The plants running with natural gas use coal powder as energy carrier for the calcination process for economic reasons. For other gas fuels, the use of the gas in the calcination furnace can be seen as standard in the short-term, because there are no economic reasons for the use of coal. The impact of this assumption is subject to a sensitivity analysis. Table 2 shows the

consumption of fuel gases for the single steps of the Pidgeon process. 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 number of companies without taking into account the individual production volume of the respective companies. The variations in gas consumption result mainly from the different heating values of the fuel gases, but to a lower extent also from the technological level of the plants which have been surveyed. For each fuel gas, a single scenario for the Pidgeon process has been calculated in order to analyse the influence of the energy source on the environmental performance. The production of producer gas is based on data from two magnesium producers. The production of the other fuel gases is taken from the ecoinvent database and does not represent Chinese conditions.

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

Production Steps	Coke Oven Gas [m <sup>3</sup> /tMg]	Semi Coke Oven Gas [m <sup>3</sup> /tMg]	Producer / Generator Gas [m <sup>3</sup> /tMg]	Natural Gas [m <sup>3</sup> /tMg]
Calcination	2600	5800	4858	1.9 t coal powder
Reduction	3600	9000	8815	1300
Refining	600	1000	1027	200
<i>Total</i>	<i>6800</i>	<i>15800</i>	<i>14700</i>	<i>1500</i>

The electricity consumption for the production steps of the Pidgeon process are given in Table 3. The data represent average consumptions (according to number of companies) for the companies which have been surveyed. The briquetting step is the most electricity intensive step. All energy needed for this process comes from electric current. The variations in electricity consumption are subject to a sensitivity analysis.

**Table 3: Electricity consumption for production steps of Pidgeon process**

Production Steps	Electricity [kWh/tMg]
Calcination	191.8
Briquetting	672
Reduction	320
Refining	48.5
<i>Total</i>	<i>1232.3</i>

A main influencing factor for the emissions from fuel combustion is the composition of the fuel itself. Due to the different origins of the fuel gases used in the Pidgeon process, the composition of the gases varies considerably. Table 4 shows the composition of the fuel gases used in the Pidgeon process.

For semi coke and coke oven gas, a large variation in gas composition can be observed. The data in the table depict the compositions used in this study, but as the data base for these

compositions is restricted to few measurements, no statistical average can be determined. The influence of this uncertainty is analysed in a sensitivity analysis.

There is no information available on the H<sub>2</sub>S and SO<sub>2</sub> content of coke oven, semi coke oven and producer gas. As all three are based on coal as raw material, it is likely that these gases contain at least a certain amount of SO<sub>2</sub>. According to Di, Nie et al. (2007), the typical sulphur content of Chinese coal is 1.05 %. Assuming that the sulphur is oxidised and remains in the fuel gas, this would lead to a SO<sub>2</sub> content of 0.017 kg per kg coal consumed for fuel production (assuming a oxidation rate of 0.81 as proposed in Di, Nie et al. (2007)). In case of producer gas, this leads to a SO<sub>2</sub> content of 0.2 vol-%, as 0.3 kg coal is needed to produce 1 m<sup>3</sup> of producer gas. For coke oven gas, the SO<sub>2</sub> content based on a coal consumption of 0.77 kg per m<sup>3</sup> gas would be 0.4 vol-%. Semi coke oven gas might be in the same range, but there is not enough information on its production to give an estimation of its SO<sub>2</sub> content. As most of the primary magnesium producers have installed desulphurisation units, the emissions of SO<sub>2</sub> are lower in these plants. The SO<sub>2</sub> emissions of the natural gas scenario, which are assumed to be comparatively high, can be seen as upper limit of SO<sub>2</sub> emissions from the Pidgeon process.

**Table 4: Average composition of fuel gases**

	<b>Coke Oven Gas</b>	<b>Semi Coke Oven Gas</b>	<b>Producer / Generator Gas</b>	<b>Natural Gas</b>
Heating Value [MJ/m <sup>3</sup> ]	16.35	8.14	5.39	36.63
CO <sub>2</sub>	3.5%	2.6%	5.0%	0.5%
H <sub>2</sub> S			0.0%	0.7%
CmHn*	2.3%	0.4%	0.3%	4.0%
O <sub>2</sub>	0.1%	2.6%	0.2%	0.2%
CO	14.5%	10.6%	27.5%	0.2%
H <sub>2</sub>	55.0%	12.1%	13.0%	0.5%
CH <sub>4</sub>	24.0%	14.2%	2.2%	92.0%
N <sub>2</sub>	0.0%	57.5%	51.8%	1.0%
SO <sub>2</sub>				0.8%

\* non-methane carbon hydrates

Apart from energy, considerable amounts of process material are consumed during magnesium production. Dolomite as raw material is quantitatively the most important. Its consumption is 10.5 kg per kg raw magnesium in a modern Pidgeon process (Table 5). Another relevant material is FeSi which is consumed in considerable amounts. The 2011 average consumption for the Pidgeon process is 1.05 kg per kg raw magnesium. Especially, its energy intensive production with an electricity consumption of 8.5 kWh per kg has a notable influence on the overall energy balance of the magnesium production (Table 6). Other materials like CaF<sub>2</sub>, refining fluxes and sulphur are consumed in comparatively small amounts. The consumption of retorts used for the reduction process is determined by its lifetime which is about 60 days. Retorts are made of steel and can be recycled. A recycling rate of 97 % is assumed which leads to small material losses in the retort life cycle. The calculation of the retort recycling includes the electricity consumption of

790 kWh per retort (average value from 3 producers) and the raw materials to balance the material losses.

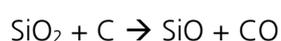
**Table 5: Material consumption of Pidgeon process**

Parameter	Quantity	Unit
Consumption dolomite per kg Mg	10.5	kg/kg
Consumption FeSi	1.05	kg/kg Mg
Consumption CaF <sub>2</sub>	0.13	kg/kg Mg
Consumption fluxes	0.096	kg/kg Mg
Consumption sulfur	0.003	kg/kg Mg

**Table 6: Energy and material consumption for FeSi production**

Parameter	Quantity	Unit
Electricity consumption	8.5	kWh/kg FeSi
Consumption anode	0.06	kg/kg FeSi
Consumption coke	1	kg/kg FeSi
Consumption quartz	1.9	kg/kg FeSi
Consumption steel	0.24	kg/kg FeSi

For the FeSi production process, the data on material consumption is based on an average of three Chinese companies which have been surveyed in 2008 (Table 6). The energy consumption and direct CO<sub>2</sub> emissions of the process are provided by BJUT based on the data survey for the Chinese LCI database. Theoretically, the main emission from the electric arc furnace where FeSi is produced is CO according to the following chemical reactions:



In reality, several further reactions lead to potential CO and CO<sub>2</sub> emissions (Andersson 2009). According to the Boudouard equilibrium, the formed CO<sub>2</sub> might also react to CO at the given furnace temperature. In the furnace, most of the CO is consumed in other reactions. Due to large uncertainties of the direct CO and CO<sub>2</sub> emissions from the furnace, we refer to the average amount of direct CO<sub>2</sub> emissions from FeSi production which has been measured at Chinese Fe-alloy plants (Zhou 2001). These emissions amount to 18.56 kg per ton FeSi. Other elements of the off-gas are amorphous condensed SiO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub>. The SiO<sub>2</sub> dust is calculated in this study. It can be filtered and used for concrete or ceramic production. As there is no information whether this is done in China, there is no further use assumed. SO<sub>2</sub> and NO<sub>x</sub> result from impurities of the raw materials and are not expected to be emitted in relevant amounts.

The upstream processes for FeSi production are either from the Chinese LCI database provided by the Centre of Materials Life Cycle Assessment (College of Materials Science and Engineering at Beijing University of Technology) as first choice and the ecoinvent database where no country

specific data is available. For the anode, a model for the production of Söderberg paste has been developed according to data from ProBas (reference year 2003).<sup>1</sup>

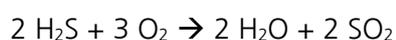
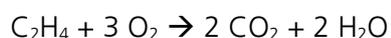
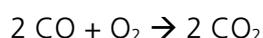
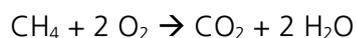
For the calculation of energy and material requirements for other upstream processes in the Pigeon process model, we referred to public databases. Most of the processes calculated in our life cycle model represent present Chinese conditions and are taken from the Chinese LCI database. Some minor material supply processes refer to global or European average data, but have only marginal effect on the overall results.

Other parameters which are relevant for modelling the Pidgeon process are process efficiency in terms of purity of the output material, estimated distances for material transports and the reference temperature gas composition and emission calculations. The melting yield of the magnesium crowns in the refining process expresses how much pure magnesium is produced per kg raw magnesium from the reduction process. These general parameters used in this study are listed in Table 7.

**Table 7: General parameters for Pidgeon process**

Parameter	Quantity	Unit
Transport dolomite to plant	70	km
Transport coal to plant	400	km
Transport CaF <sub>2</sub> to plant	800	km
Transport FeSi to plant	200	km
Temperatur for calculation of gas masses	298.15	K
Melting yield Mg crowns (pure Mg vs. raw Mg)	97.5	%
S content coal	0.0105	kg/kg

The emissions of CO<sub>2</sub> and SO<sub>2</sub> from fuel combustion during the Pidgeon process are calculated according to the stoichiometric equations for each component of the fuel gases. The reactions that occur during combustion are:



The oxidation rate for combustion is assumed to be 0.97. NO<sub>x</sub> and particles are calculated according to factors from Chinese Pidgeon process model made by BJUT (Gao, Nie et al. 2009). Chapter two of Volume two of the IPCC Guidelines (Energy → Stationary Combustion) provides the approaches for calculating emissions resulting from the stationary combustion of coke oven gas used in primary production of magnesium (Gómez, Watterson et al. 2006). It has been

<sup>1</sup> ProBas is a German online library on LCA data ([www.probas.umweltbundesamt.de](http://www.probas.umweltbundesamt.de)).

discussed in this project, whether the use of coke oven gas can be evaluated by using emission data from IPCC. The IPCC is assigned to provide guidelines for the national greenhouse gas inventories of member states. These guidelines primarily include the provision of methods to calculate emission figures for member states on national level. Therefore, aggregate data is used as inputs for these calculations. It is explained how and when to use which approach. The tier 1 approach requires data on the amount of combusted fuel and a default emission factor. Under tier 2, the default emission factor of tier 1 is replaced by country specific emission factors. Tier 3 calculates emission by using input data depending on the used combustion technology. In order to use the mentioned methods to generate national inventories, IPCC also provides standard default values for emission factors in its own emission factor data base<sup>2</sup>.

The default carbon content ( $c_k$ ) for coke oven gas, for instance, is held here with 12.1 kg/GJ. Specific values for China are not provided for. Hence, emissions for China cannot be calculated under the tier 2 approach using only IPCC data. The following equation depicts the calculation of the default effective CO<sub>2</sub> emission factor ( $EF_{CO_2,k}$ ). The IPCC default value for coke oven gas is 44,400 kg/TJ (with  $\eta=1$ )<sup>3</sup>.

$$EF_{CO_2,k} = c_k \times \eta \times \frac{44}{12 \times 1000}$$

According to the IPCC Guidelines the amount of CO<sub>2</sub> emissions can now be obtained by multiplying the emission factor with the consumed amount of fuel ( $AD_{fuel}$ ):

$$Q_{GHG,fuel} = AD_{fuel} \times EF_{GHG,fuel}$$

As explained above the tier 1 and 2 methodologies are rather inapplicable to estimate greenhouse gas emissions resulting in the primary production of magnesium, as these methodologies do not incorporate specific data on China or the Pidgeon Process. The IPCC does not supply input data on Pidgeon Process for the technology based tier 3 approach, which also hampers the usage of a process-based emission calculation.

### 3.2.3 Sensitivity Analysis

#### Substitution principle for coke oven and semi coke oven gas

The calculation of the standard scenario is based on an allocation for the production of coke oven gas and semi coke oven gas according to the energetic contribution of the fuel gases to the entire production from the (semi) coke plant. The emissions are completely accounted to the Pidgeon process. As at present, these fuel gases are treated as waste from the (semi) coke plant and provided to the magnesium producers for free, the waste gas which would be released to the atmosphere without use 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

<sup>2</sup> [http://www.ipcc-nggip.iges.or.jp/EFDB/find\\_ef\\_s1.php](http://www.ipcc-nggip.iges.or.jp/EFDB/find_ef_s1.php)

<sup>3</sup> Default Value 95% confidence interval is 37,300 kg/TJ (lower) and 54,100 kg/TJ (upper).

production which is an upstream process for the FeSi production is burdened with the full environmental loads in this scenario.

Furthermore, in order to evaluate uncertainties due to variations in some of the process parameters, a sensitivity analysis has been conducted for the composition of fuel gases, consumption of fuel gases and electricity consumption. The influence of the variation of these parameters on the results is shown in chapter 3.4.1.

The sensitivity of the results has been calculated for:

### Gas composition semi coke oven gas and producer gas

The emissions of the combustion process depend on the composition of the fuel gases. The alternative contents of gas components are listed in Table 8. In case of semi coke oven gas, the standard composition is based on measurements by the University of Science and Technology Beijing, the alternative composition is reported by a Chinese company. The data on producer gas are both from Chinese companies.

**Table 8: Alternative composition of semi coke oven and producer gas**

	Semi Coke Oven Gas		Producer / Generator Gas	
	standard	alternative	standard	alternative
CO <sub>2</sub>	2.6%	7.5%	5.0%	4.4%
H <sub>2</sub> S	0.0%	0.0%	0.0%	0.1%
C <sub>m</sub> H <sub>n</sub>	0.4%	1.0%	0.3%	0.2%
O <sub>2</sub>	2.6%	0.3%	0.2%	0.1%
CO	10.6%	16.0%	27.5%	26.9%
H <sub>2</sub>	12.1%	24.5%	13.0%	13.7%
CH <sub>4</sub>	14.2%	10.4%	2.2%	1.9%
N <sub>2</sub>	57.5%	40.4%	51.8%	52.6%

### Electricity consumption FeSi production

For electricity consumption of the FeSi production, values from 7.8 kWh to 9.0 kWh per kg FeSi are reported by FeSi producers. As FeSi production is an energy intensive process with considerable influence on the overall balance for magnesium production, we evaluated the effect of higher or lower energy consumption.

### Melting yield

One indicator for process efficiency is the melting yield of magnesium from reduction. This can be expressed by considering the material loss during the refining process due to impurities of the raw magnesium. The standard value for this yield is 97.5 %. As a yield of 93 % has been reported as well, we analyse the impact of such decrease in efficiency.

## 3.3 Electrolysis

### 3.3.1 Process Steps

Electrochemical processes to make magnesium are based on salts containing chloride which can be found naturally or are transformed from other raw materials like serpentine, magnesite, bischofite or carnallite. The magnesium chloride salts are dried in different processes in order to gain anhydrous  $\text{MgCl}_2$ , either in solid or molten form.

All of the above mentioned raw materials can be used for this procedure. However, the raw materials have to be converted into chlorinated salts first, except of bischofite and carnallite. This is done by adding a hot hydrochloric acid solution (HCl), resulting in an aqueous solution of  $\text{MgCl}_2$ . The solution has to be dried afterwards and finally put into the electrolysis cell. A cell exists of a fire-resistant ceramic crucible in which graphite anodes and steel cathodes are inserted. Modern diaphragmless electrolytic cells essentially consist of at least two chambers - the electrolyte chamber(s) and the metal collection chamber, both separated by a refractory partition wall.

The electrolyte is located within the cell and consists of a mixture of different salts, primarily  $\text{MgCl}_2$ , KCl, NaCl and  $\text{CaF}_2$ . It enables the current flow between the electrodes and therefore should have minimal ohmic resistivity. Other important requirements are low costs as well as a sufficient density, so that the lighter magnesium is able to float.

During operation, the raw material magnesium chloride is split into magnesium and chlorine ( $\text{Cl}_2$ ) by the current flow. Electrolyte filled with the chlorine gas adjacent to the anodes has lower density than the bulk electrolyte, which results in the melt circulation. A suitable arrangement of the electrodes and the partition design guide the electrolyte with magnesium globules into the metal collection chamber. Chlorine gas is evacuated through a collector duct in the electrolyte compartment/s and transferred for further treatment. The chlorine gas is extracted consistently and can be used for the production of new HCl and chlorination of the minerals. Afterwards, the magnesium is refined under further addition of salts. It still contains normally up to 2% of electrolyte, magnesium oxide and nitride after the electrolysis.

The protective atmosphere for molten magnesium consists of a carrier gas like nitrogen, carbon dioxide or argon and a protection gas in low concentration. Apart from smaller amounts of gas that react with the surface of the melted magnesium, the gas usually is released into the atmosphere. Most common protection gas in electrolysis plants as well as magnesium cast plants has been sulphur hexafluoride ( $\text{SF}_6$ ). As it is the most potent greenhouse gas known, its use has been restricted in the EU. Followed by growing efforts to reduce GHG emissions, alternatives for  $\text{SF}_6$  have been developed. A well-known alternative is sulphur dioxide ( $\text{SO}_2$ ). It has no effect on the greenhouse mechanism, but it is hazardous to livings and eco systems when concentration in air reaches a certain level. In practice, concentration of  $\text{SO}_2$  as protective agent is about 2 vol.-% which is within the tolerable concentration in such plants. Another alternative is tetrafluoroethane (R134a) which also commonly used as cooling agent. Its  $\text{GWP}_{100}$  still is 1430

CO<sub>2eq</sub>. Regarding these environmental impacts, gases containing fluorine and sulfur cannot be seen as final solution. Therefore, new alternatives are tested like the use of CO<sub>2</sub> snow (Karger 2006).

### 3.3.2 Life Cycle Inventory for Electrolysis

During the past decade, magnesium supply has changed from electrolysis based to silicothermic based. Due to this development, production sites in Norway and Canada have been closed. As LCA publications evaluating electrolysis are based on data from the Norwegian plant which used electricity based on water power, the results of these studies do not represent today's state of this technology.

In our study, we developed a model for an electrolysis which represents today's conditions. The data on energy consumption is based on an update of Aghion and Bartos (2008). Compared to 2008, the electrolysis process presented in this report has changed from an energy supply based on oil to an energy supply based on natural gas (Aghion 2012; Kotlovsky 2013). Electricity production from gas power plants and heat supply from industrial furnace are taken from the ecoinvent database for the European context (UCTE net in case of electricity). Moreover, R134a replaced SF<sub>6</sub> as cover gas (DSM 2006). Data on the production of R134a have been taken from McCulloch and Lindley (2003).

The data input for electrolysis are listed in Table 9. The process steps of the electrolysis are shown in Figure 9. The raw material for magnesium production in this case is carnallite (MgCl<sub>2</sub>·KCl·6H<sub>2</sub>O). The consumption of carnallite has been calculated according to the stoichiometry of the process. In this type of electrolysis plant, two by-products are produced: liquefied chlorine (Cl<sub>2</sub>) and KCl-rich salt. The first has a wide range of potential uses and the second one can be converted to potassium fertilizer. The amount of Cl<sub>2</sub> is up to 2.5 kg per kg magnesium. Electrolytic processes based on other resources than carnallite have less or no Cl<sub>2</sub> output. For the spent electrolyte, the ratio is about 5.5 kg per kg magnesium. This by-product is not relevant for electrolytic processes where MgCl<sub>2</sub> is fed to the cells. The data for the substituted products are taken from the ecoinvent database. In case of Cl<sub>2</sub>, a process representing a production mix of liquefied Cl<sub>2</sub> in Europe is used as substituted product.

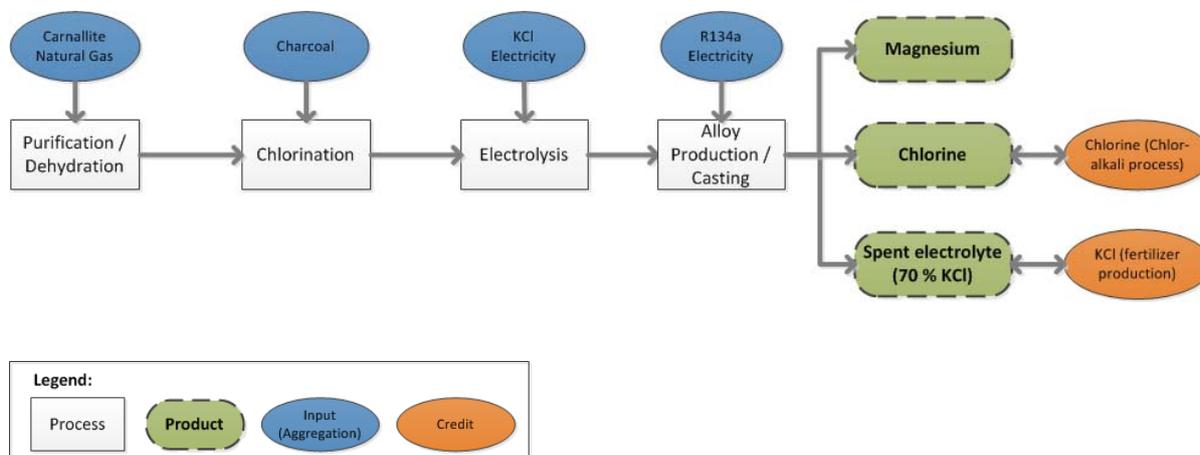
In this type of electrolysis, magnesium oxide (MgO) is formed as an impurity during dehydration, Our actual consumption levels of coke are much less than reported for example in the ecoinvent database for the Norsk Hydro plant. The respective coke consumption is included in the model, but the figure cannot be published in this report since it is confidential. Concerning the CO<sub>2</sub>/CO equilibrium in the calcination process, there are numerous reactions that take place in the chlorination chambers and the carbon can be consumed by reaction with MgO, air, water, sulfates and other impurities. Theoretically, the predominant reactions are those in which carbon dioxide is formed (Kotlovsky 2013). Thus, we assumed that the carbon is entirely converted to CO<sub>2</sub>. The CO<sub>2</sub> emissions from graphite anode consumption are expected to contribute less than 1 % of the overall emissions and are neglected in the model. In practice, the off gases are not

released to the atmosphere as is, as they are treated in wet alkali scrubbers. That is that some of the CO<sub>2</sub> (be it from the reaction or from the ambient dilution air) is converted to calcium carbonate.

**Table 9: Life cycle inventory for magnesium electrolysis**

Parameter	Quantity	Unit
<b>Dehydration &amp; Chlorination</b>		
Carnallite	11.4	kg/kg Mg
Coke*		
Energy* (heat and electricity - natural gas)	55.4	MJ/kg Mg
<b>Electrolysis</b>		
Electricity (natural gas)	14	kWh/kg Mg
<b>Casting</b>		
R134a	0.000835	kg/kg Mg
Electricity (natural gas)	1	kWh/kg Mg
<b>Others</b>		
Electricity (natural gas)	3	kWh/kg Mg

\* Figures on coke consumption and the share of heat and electricity for dehydration and chlorination are confidential



**Figure 9: Inputs and process steps of electrolysis process**

### 3.3.3 Sensitivity Analysis

Contrary to the SF<sub>6</sub> gas, R134a is much less stable and is easily decomposed at high temperatures when it comes in contact with Mg surface. The destruction factor may be as high as 70% with the primary destruction products like HF and COF<sub>2</sub>. Thus, the use of 1430 kg CO<sub>2eq</sub> per kg R134

for the characterization factor can be seen as conservative assumption. As the use of R134a has low influence on the results of the impact assessment, the changes in the overall balance due to destruction reactions can be seen as insignificant and no sensitivity analysis is needed for this subject.

Though, data on material consumption are uncertain except from cover gas use, this data is not seen as relevant for the result of the impact assessment.

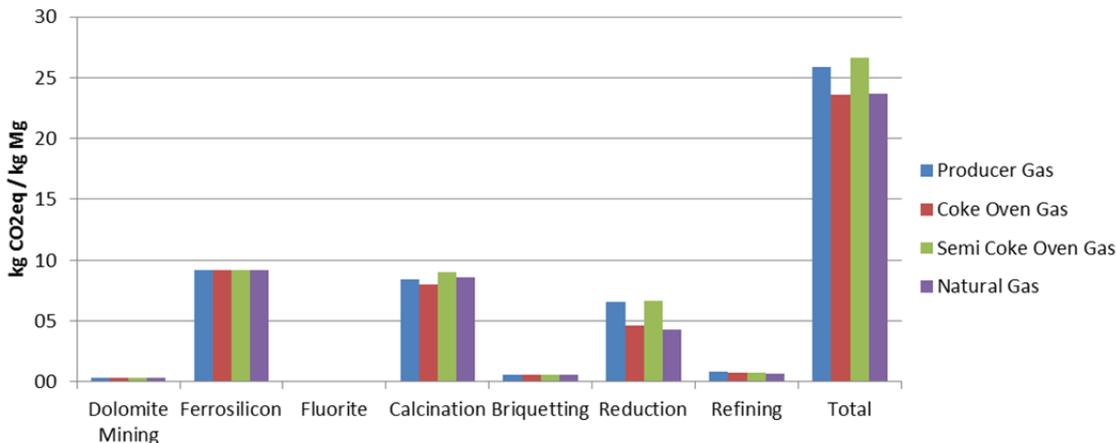
### **3.4 Environmental Indicators for Primary Magnesium Production**

#### **3.4.1 Results for Pidgeon Process**

For the evaluation of the Pidgeon process, we calculated the results for the impact categories described in chapter 2. The model 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. As the FeSi production is an energy and material intensive process which leads to high emissions, the results for this material are shown as separate process step. For better transparency, the impact of the production of the  $\text{CaF}_2$  is also shown separately. As for FeSi and fluorite production as well as for dolomite mining and briquetting, all Mg production options are based on equal input data, the results are the same for all scenarios.

Figure 10 shows the greenhouse gas emissions of the Pidgeon process. The fuel gas and electricity consumption as well as transports are allocated to the single process steps. Clearly, the production of FeSi, the calcination of dolomite and the reduction itself are the most GHG-emission intensive life cycle steps. Compared to former studies (Ramakrishnan and Koltun 2004; Ehrenberger, Schmid et al. 2008; Gao, Nie et al. 2009), the influence of these process steps has changed. In these studies, the reduction process has been the dominant process followed by FeSi production and calcination. Efforts in increasing the efficiency of the reduction process lead to a notable decrease of emissions. Emissions of FeSi production amount to 9.2 kg  $\text{CO}_{2\text{eq}}$  per kg magnesium. Results for the calcination process vary from 8.0 to 8.6 kg  $\text{CO}_{2\text{eq}}$  / kg Mg for the scenarios natural gas, producer gas and coke oven gas. The value for the semi coke oven gas scenario is 9.0 kg  $\text{CO}_{2\text{eq}}$  / kg Mg which is higher than the result for coal based calcination of the natural gas scenario. The emissions for the reduction process range from 4.3 (natural gas) to 6.7 (semi coke oven gas) kg  $\text{CO}_{2\text{eq}}$  / kg Mg. This reflects the different properties of combustion of the different fuel gases which vary in terms of heating value and carbon content. Dolomite mining (0.3 kg  $\text{CO}_{2\text{eq}}$  / kg Mg), fluorite production (0.1 kg  $\text{CO}_{2\text{eq}}$  / kg Mg), briquetting (0.57 kg  $\text{CO}_{2\text{eq}}$  / kg Mg) and refining (0.67 to 0.80 kg  $\text{CO}_{2\text{eq}}$  / kg Mg) play a minor role in the overall balance.

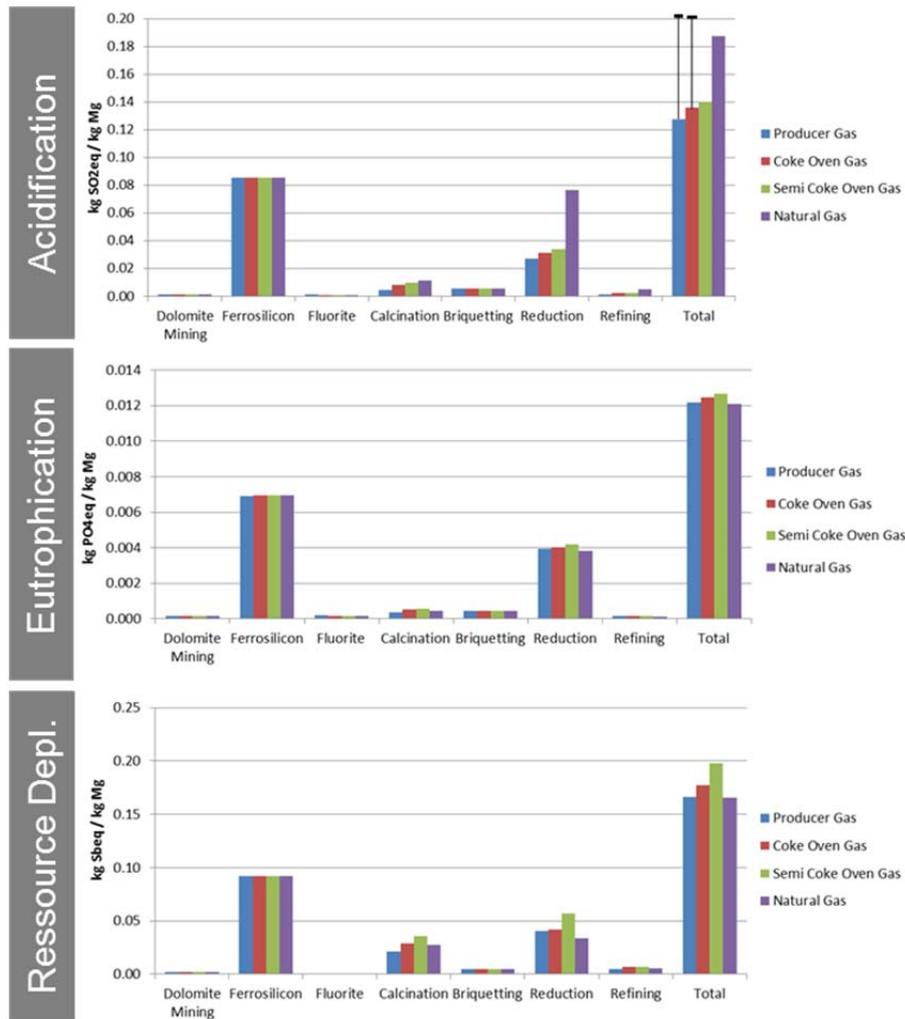
The weighted result for greenhouse gas emission of the Pidgeon process in 2011 is 25.8 kg  $\text{CO}_{2\text{eq}}$  / kg Mg. The weighting considers the annual production volume of each of the scenarios as listed in Table 1.



**Figure 10: Greenhouse gas emissions of Pidgeon process**

The results for the impact categories acidification, eutrophication and resource depletion are shown in Figure 11. Regarding the contribution to the overall result, FeSi production is a dominant factor for all categories due to its high energy and material consumption. For the process steps of the Pidgeon process itself, the composition of the fuel gases (and of coal in case of calcination in the natural gas scenario) has major influence on the emissions to air. The acidification potential of the combustion of natural gas in the reduction furnace results from its H<sub>2</sub>S and SO<sub>2</sub> content. This leads to the highest acidification potential of all scenarios. The bars for producer and coke oven gas indicate the estimation of SO<sub>2</sub> emissions from the use of these gases based on the sulphur content of the coal which is used as raw material for the gas production. In both cases, the acidification potential increases considerably to about 0.2 kg SO<sub>2eq</sub>. These emissions do not consider the use of desulphurization installations which would decrease the direct SO<sub>2</sub> emissions from the magnesium plant by ca. 90 %. Since January 2012, the Chinese regulations provide maximum emissions of 400 mg SO<sub>2</sub> per kg off-gas and maximum immissions of 0.5 mg per m<sup>3</sup> air in the direct surrounding of the magnesium plant (Standardization Administration of China (SAC) 2010). Thus, it is likely that further installations of desulphurization units lead to less SO<sub>2eq</sub> emissions than indicated from the estimations shown in this report. The results for eutrophication contain a default factor for emissions of NO<sub>x</sub> which has been accounted to the reduction process, though a certain share of these emissions results also from calcination and refining.<sup>4</sup> The overall emissions with eutrophication potential of the FeSi production is in the same range as the rest of the Pidgeon process (0.055 PO<sub>4eq</sub> / kg Mg). In case of depletion of resources, semi coke oven gas shows high coal consumption which results in highest impact for this scenario. The detailed results are listed in Annex I).

<sup>4</sup> Emissions are estimated according to the calculations by Gao, Nie et al. (2009)



**Figure 11: Results for acidification, eutrophication and resource depletion for the Pidgeon process**

Figure 12 shows the results for the impact assessment of the Pidgeon process in terms of direct emissions from the Pidgeon process itself and indirect emissions from energy and material supply and transport of FeSi and CaF<sub>2</sub>. The figures for raw material supply include the production of dolomite, FeSi, CaF<sub>2</sub>, retorts and other process materials. The emissions for the material supply are the same for all Pidgeon process scenarios. The energy supply represents the electricity and fuel gas production. For the natural gas scenario, the production of coal is also included in this figure, as coal is used as energy carrier for calcination.

In case of the greenhouse gas emissions, the direct emissions from the Pidgeon process amount to 13.4 kg CO<sub>2</sub>eq per kg magnesium (weighted average) which is 51 % of the total emissions (Figure 13). The upstream processes of material supply have a share of 38 % of the total greenhouse gas emissions mainly coming from FeSi production. The contribution of energy supply differs between the scenarios, as the production of fuel differs as well. The contribution of

electricity is equal for all scenarios (1.1 kg CO<sub>2eq</sub>). The contribution of transports of FeSi and CaF<sub>2</sub> has little influence on the total emissions.

For the assessment of potential eutrophication and acidification, the raw material supply is dominant as well. The natural gas scenario shows very high SO<sub>2eq</sub> emissions. This results from the combustion of coal containing sulfur during the calcination process as well as from the fact that in the standard composition of fuel gases (Table 4) H<sub>2</sub>S and SO<sub>2</sub> contents are only reported for natural gas. The estimations on SO<sub>2</sub> contents of semi coke and coke oven gas result in higher a higher acidification potential for these two scenarios (as indicated by the black bars in Figure 7). The material consumptions which contribute to the potential resource depletion are included in the upstream processes of raw material and energy supply and transport.

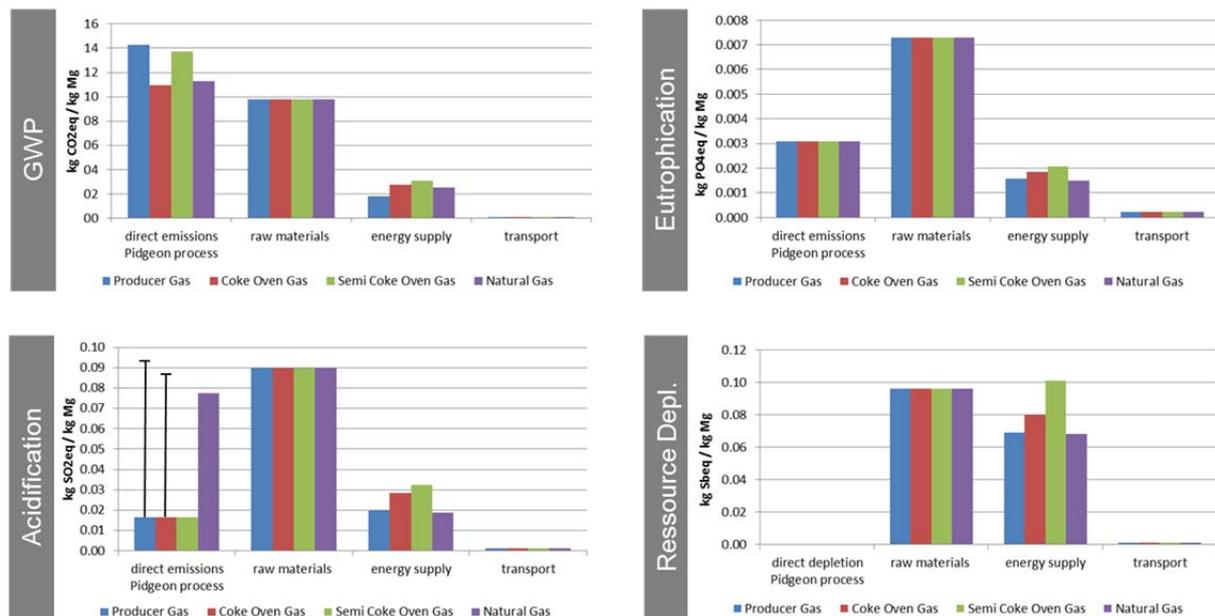


Figure 12: Results of impact assessment for Pidgeon process in terms of direct and indirect emissions

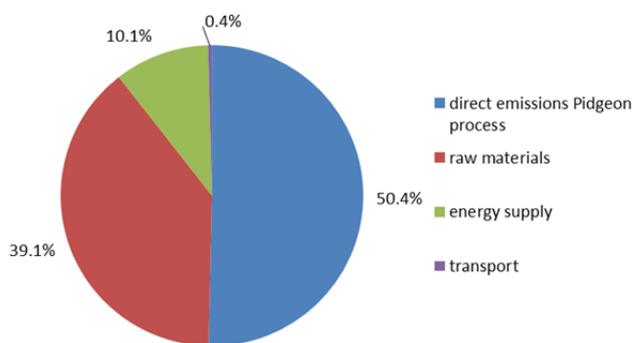
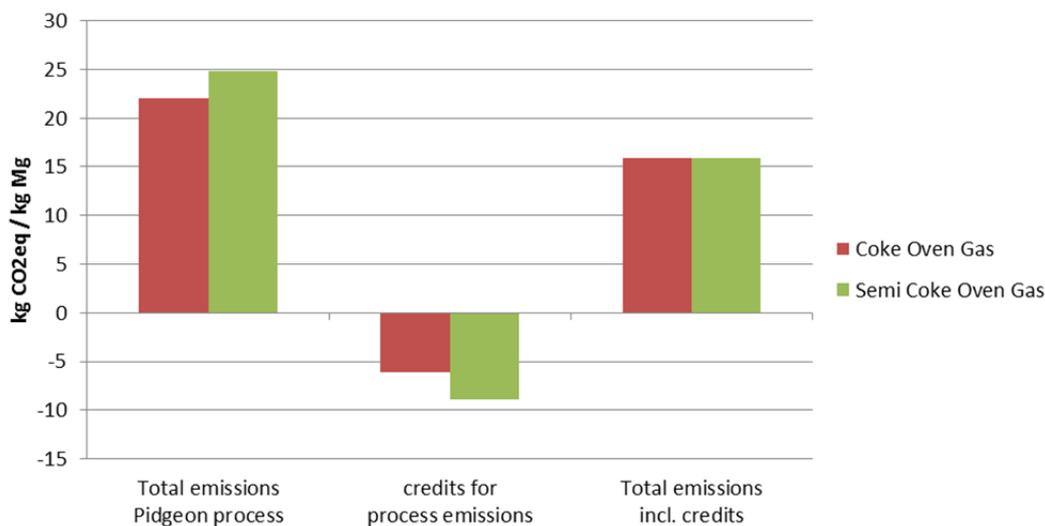


Figure 13: Contribution of direct and indirect emissions to GHG emissions

The results of the sensitivity analysis have been calculated according to the input data described in chapter 3.2.3. As the main focus of this study is on the emissions of greenhouse gases as environmental indicator, mainly the results for this category are presented in the following.

**Substitution principle for coke oven and semi coke oven gas**

In the present situation of coke and semi coke production, the resulting gases are waste from these product systems. The economic incentives and the legal requirements of finding a use for these gases are the main drivers for the wide use of these gases for primary magnesium production. In order to reward the use of production waste from the coke and semi coke industry, an alternative methodological approach to the energetic allocation used in the standard scenario is applied. When the use of the waste gases for coke and semi coke production is credited, several changes compared to the standard scenario have to be regarded. First, the production of the gases is not accounted to the magnesium product system, while the coke production in the FeSi system additionally gets the previously allocated burdens for gas production. Second, the emissions which would have been emitted into the air without use are credited to the magnesium product system. By applying this approach, the GHG emissions from both fuel gas scenarios drop to about 15.9 kg CO<sub>2eq</sub> / kg Mg (Figure 14). The weighted average of the Pidgeon process decreases to 19.9 kg CO<sub>2eq</sub> / kg Mg.

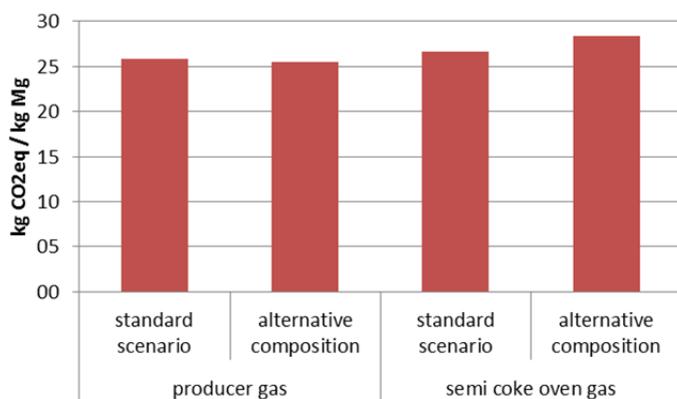


**Figure 14: Results for the greenhouse gas emissions from coke oven and semi coke oven gas scenarios in case of substitution of emissions**

**Gas composition semi coke oven gas and producer gas**

The changes in greenhouse gas emissions for the variation in composition of producer and semi-coke oven gas are depicted in Figure 8. For producer gas, the alternative gas composition leads to a decrease of 2 % in case of greenhouse gas emissions due to the lower content of CO<sub>2</sub>, CH<sub>4</sub> and

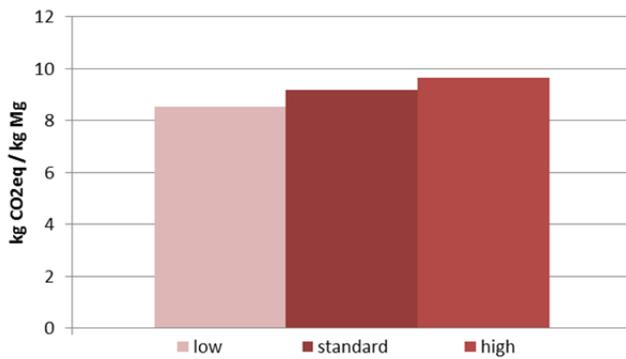
CO. On the contrary, the alternative composition of semi coke oven gas shows higher contents of CO<sub>2</sub> and CO which results in an increase of 7 % to almost 28 kg CO<sub>2eq</sub> / kg Mg. The highest difference between standard and alternative scenario results from the increase of H<sub>2</sub>S content in the alternative producer gas scenario. An increase of 29 % of acidification potentials can be observed. Again, the use of desulphurization installations would decrease these emissions considerably. Nevertheless, these results show that the composition of fuel gases is a relevant factor for the assessment of the Pidgeon process., though it is not as important as the methodological choice of crediting the use of waste gases from other product systems as seen above. The results for this process can be more precise, if more data on this composition would be available.



**Figure 15: Changes in greenhouse gas emissions from different gas compositions for producer gas and semi coke oven gas**

### Electricity consumption FeSi production

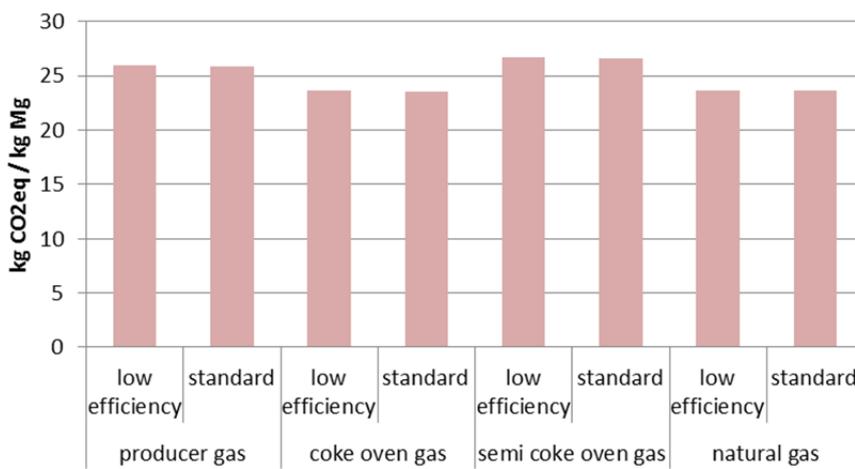
The difference in greenhouse gas emissions for the variation of electricity consumption in the FeSi production from 7.8 kWh to 9.0 kWh is depicted in Figure 16. The emissions range from 8.5 to 9.6 kg CO<sub>2eq</sub> / kg Mg. For all impact categories, the emissions decrease by 7 % in case of lower electricity consumption and increase by 7 % for higher consumption as there is a linear dependence from the input parameters. Generally, this uncertainty in FeSi production influences the overall results for the Pidgeon process notable. Though magnesium producers do not influence the FeSi production process directly, those companies which do not depend on a specific FeSi supplier in a production network, for instance, can influence the performance indirectly by choosing suppliers according to their efficiency.



**Figure 16: Greenhouse gas emissions in dependence of energy consumption in the FeSi production**

**Melting yield 93 % instead of 97.5 %**

The variation of the melting yield of the Pidgeon process from 97.5 % to 93 % leads to an increase of around 1 % in the impact categories. Figure 17 shows the changes for the greenhouse emissions. Compared to gas composition and electricity consumption of FeSi production, the efficiency of the Pidgeon process has less influence on the overall result.



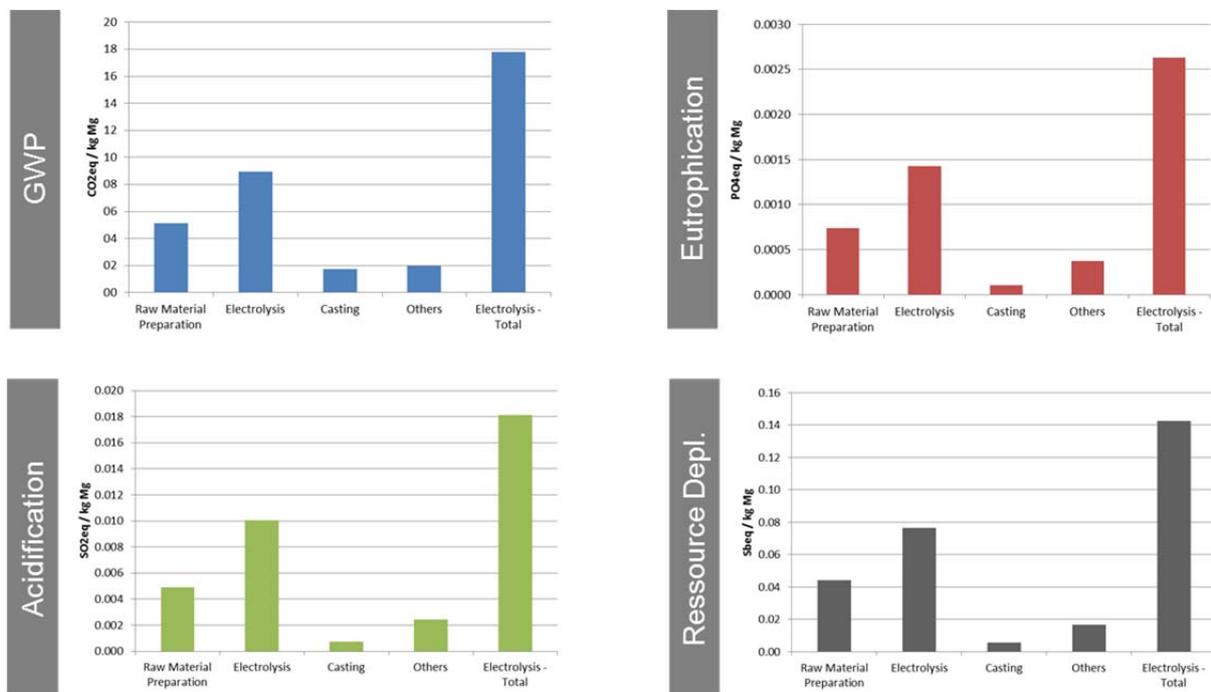
**Figure 17: Changes in greenhouse gas emissions due to variation of efficiency of the Pidgeon process**

**3.4.2 Results for Electrolysis**

For all impact categories, the electrolysis step itself is the dominant process followed by the preparation of the raw materials. Main factor for emissions and resource depletion is the consumption of electricity. The contribution of energy supply is 94 % for the global warming

potential, 97 % for eutrophication, 98% for acidification and 99.8 % for resource depletion. For the global warming potential, the overall emissions amount to 17.8 kg CO<sub>2eq</sub> / kg Mg. The contribution of electricity production is about 13.8 kg CO<sub>2eq</sub> / kg Mg. Aghion and Bartos (2008) reported 21 kg CO<sub>2eq</sub> / kg Mg only considering the energy consumption of the process. Thus, the switch of fuel for the energy supply from oil to gas has led to a notable decrease of greenhouse gas emissions.

The contribution of the cover gas R134a which is used in the casting process has little influence on the overall greenhouse gas balance. Compared to the former use of SF<sub>6</sub>, which lead to additional 22.8 kg CO<sub>2eq</sub> / kg Mg (Aghion and Bartos 2008), the use of R134a causes considerable less GWP (1.1 kg CO<sub>2eq</sub>/ kg Mg) though this compound still is a potent greenhouse gas.



**Figure 18: Results of impact assessment for electrolysis**

As described in chapter 3.3.2, there are two by-products for a carnallite based electrolysis: Cl<sub>2</sub> and KCl. The substitution of the production of these products in other processes can be credited in the impact assessment. Figure 19 shows the results of the impact assessment for the electrolysis as reported above. The detailed results are presented in Annex I). The credits for the conventional production of Cl<sub>2</sub> via chlor alkali electrolysis and of KCl as fertilizer are subtracted from these results. This method leads to net total results for the electrolysis process. In case of GWP and resource depletion, the results decrease slightly. For the eutrophication and acidification categories, the conventional production of Cl<sub>2</sub> has a much higher impact which results in net emission savings. The data for the substituted products are taken from the ecoinvent database 2.2 and are not up-to-date. Modern production routes for Cl<sub>2</sub> and KCl probably lead to much

lower emissions at least in the case of greenhouse gases and thus the credits would decrease as well in the climate change category.

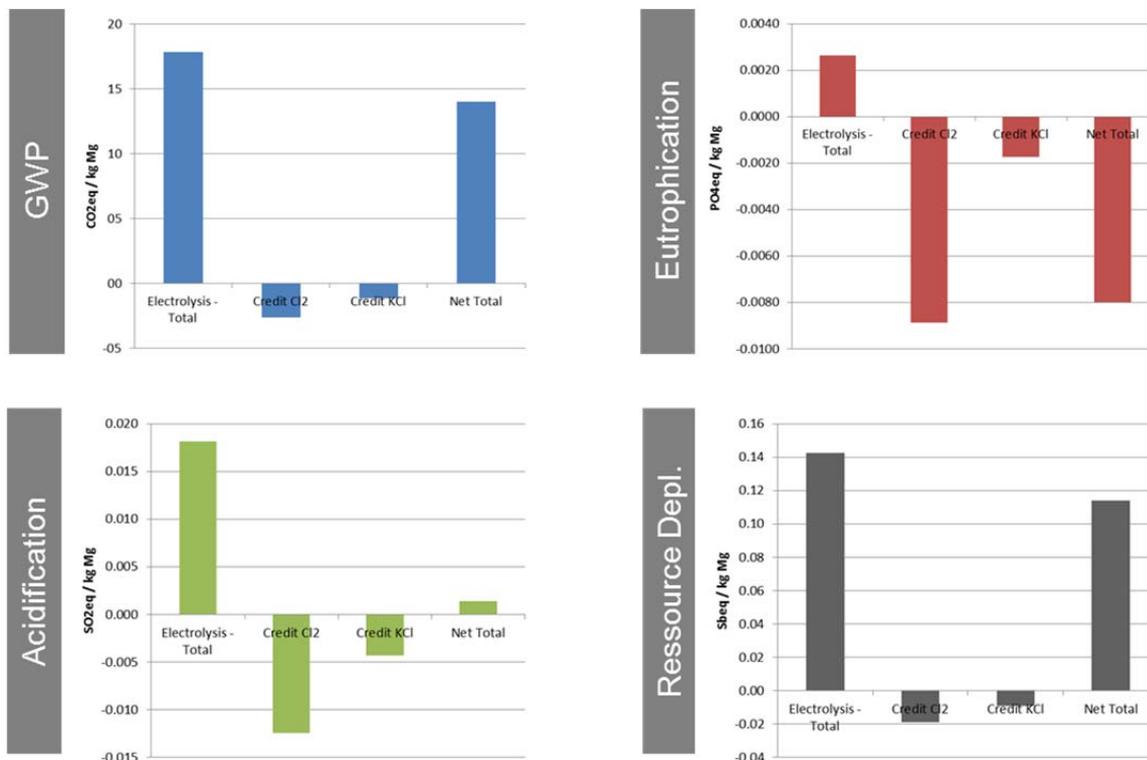


Figure 19: Impact assessment for electrolysis including credits for by-products

### 3.4.3 Comparison of Results for GHG Emissions of Primary Magnesium Production

During the past years, there have been various data published describing the CO<sub>2</sub> emissions of the Pidgeon process. Due to the high energy consumption and the use of coal as energy carrier, first assessments of the Pidgeon process showed a global warming potential of about 42 kg CO<sub>2eq</sub> / kg Mg (Ramakrishnan and Koltun 2004). Figure 20 shows an overview of references treating primary magnesium production. The figures are divided into thermal and electrolytic production. Data for thermal production refer to the Chinese Pidgeon process apart from Franca and Pereira Brito (2011) and Haberling, Franca et al. (2013). The results for the Pidgeon process with coal as only energy source range from 37 to 47 kg CO<sub>2eq</sub> / kg Mg. These data come widely from a DLR own survey made 2008 when producers in China were interviewed (Ehrenberger, Schmid et al. 2008).<sup>5</sup> The use of gaseous fuels as well as technical improvements enhances the efficiency of the

<sup>5</sup> Companies that have been interviewed in 2008: Taiyuan Tongxiang Magnesium CO. Ltd; Shanxi Wenxi Yinguang Magnesium Group; Ningxia Huiye Magnesium Marketing co. Ltd; Ningxia Huayuan

process. In 2011, all primary magnesium producers in China use gaseous energy carriers. Additionally, an improved energy management by high temperature air combustion (HTAC) technology is standard in the magnesium industry. The present data gathered by DLR and CMA are provided by Mg-producers. These data indicate that the global warming potential for the production conditions in 2011 amounts to 25.8 kg CO<sub>2eq</sub>/ kg Mg. When the use of coke oven and semi coke oven gas as waste from other product systems is credited, the average global warming potential per kg magnesium is 19.9 kg CO<sub>2eq</sub>.

For the silicothermic process in Brazil, a modified type of Bolzano Process, the authors have calculated CO<sub>2eq</sub> emissions of 10.1 kg per kg magnesium (Haberling, Franca et al. 2013). This includes a credit for the CO<sub>2</sub> uptake by eucalyptus trees that are used as biomass in the production process.

For the electrolytic process the emissions depend widely on the energy carrier used. The global warming potential based on up-date information is 17.8 kgCO<sub>2eq</sub>/ kgMg (IMA 2013) when no credits for by-products are given. With credits for the process by-products, the global warming potential is 14.0 kg CO<sub>2eq</sub> per kg magnesium. This refers to the use of natural gas for thermal heat for dehydration and the production of electricity. When only using sustainable energy carrier (water power) this figure drops dramatically to the range of 6 kgCO<sub>2eq</sub>/ kgMg (Albright and Haagenen 1997).

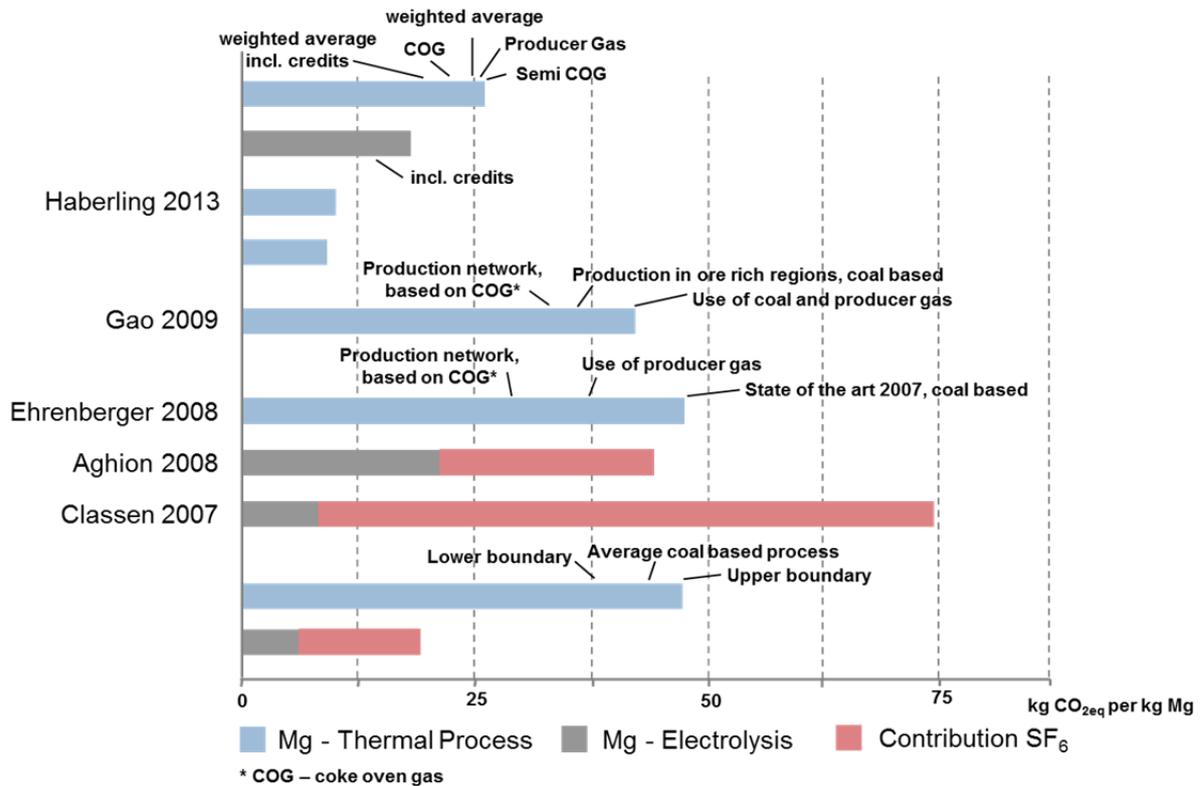
One influencing factor for the results of magnesium production is the use of sulfur hexafluoride (SF<sub>6</sub>) as cover gas. Western electrolysis plants have been using SF<sub>6</sub> (Albright and Haagenen 1997; Classen, Althaus et al. 2007; Aghion and Bartos 2008) as described above. The influence of the SF<sub>6</sub> in the greenhouse gas balance is indicated by the red colored bars in Figure 20. The low emissions from the electrolysis described in Albright and Haagenen (1997) result from the high share of hydro power which is taken into account for the Norwegian plant which has been studied in that article. Taking into account the contribution of SF<sub>6</sub>, the greenhouse gas emissions of electrolysis reach in Aghion and Bartos (2008) in the range of the Pidgeon process. Thus, using alternatives like R134a improves the greenhouse gas balance notably.

New projects in Norway or Canada<sup>6</sup> try to use the above mentioned advantage to provide ecologically competitive Mg production routes. These and other projects are today in a concept phase.

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Metallurgical Industry Corporation; Shanxi Wenxi Hongfu Magnesium Co. Ltd; Shanxi Qizhen Magnesium Co. Ltd.

<sup>6</sup> Even if it is a silicothermic process, the GOSSAN project addresses water power for electricity used. They plan CO<sub>2</sub> emissions of less than 10 kgCO<sub>2eq</sub>/kgMg Gossan Resources Ltd. (2012). Lowering of CO<sub>2</sub> Emissions for Magnesium Production by Gossan-Zuliani Process. P. R. O. Inc. Mississauga, Ontario, Canada..



**Figure 20: Overview of literature data and own results on greenhouse gas emissions for primary magnesium production**

The results for energy consumption and greenhouse gas emissions differ widely depending on the used technology and the energy situation. Table 10 gives an overview for silicothermic and electrolytic processes. Also an average value for aluminium is added (Note: Generally less magnesium is needed – up to 30% - to fulfil the same technical requirement in a component compared to aluminium (see part II of this study).

**Table 10: Overview of data for energy consumption and greenhouse gas emissions for typical primary Mg production processes and Al**

	Energy Consumption (excl. upstream processes) [kWh/kgMg]	GHG emission [kgCO <sub>2eq</sub> /kgMg]
Silicothermic PIDGEON (IMA 2012)	>37	25.3
Electrolysis (Gas) (IMA 2012)	28	18.2
Electrolysis (Waterpower) (Albright 1997)	35	19 (w/o SF <sub>6</sub> : 6)
Silicothermic BOLZANO/BRASIL (Haberling, Franca et al. 2013)	20.8	10.1
Silicothermic GOSSAN (project) (Gossan Resources Ltd. 2012)	21.5	9.1

### 3.5 Comparison to Primary Aluminium Production

Aluminium is produced commercially only by electrolysis. The total production amounted to 45 Mio t in 2012.<sup>7</sup> This is multiple times more than magnesium supply. Unlike for magnesium, the primary aluminium production is distributed more or less equally in different world regions. Most aluminium is production in North America and Europe.

The European Aluminium Association (EAA) started to analyze environmental impacts from primary aluminium production in the mid-1990s. The EAA published reports on the environmental profile of the European aluminium industry in 1996, 2000, 2005 and 2008 (European Aluminium Association 2008). The 2008 study which included data from 2005 as reference reports CO<sub>2eq</sub> emissions of 9.7 kg per kg primary aluminium produced in Europe. This is 22 % less compared to 2000 (reference year 1998). The results represent average figures of 90 % of aluminium produced in Europe.

Further studies have been published for the primary aluminum production in Germany (Kolb 2004; Scholz AG 2010), China (Gao, Nie et al. 2009) and USA (da Silva, d'Souza et al. 2010). In general, energy consumption and emissions from European plants are lower than the global average. Figure 21 depicts the most important figures form literature on primary aluminium production.

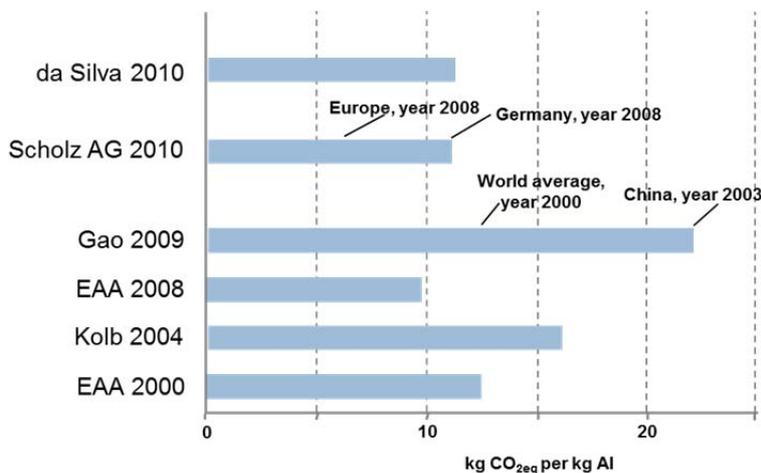


Figure 21: Overview on greenhouse gas emissions for primary aluminium

<sup>7</sup> Statistics on primary aluminium production from the International Aluminium Institute at [www.world-aluminium.org](http://www.world-aluminium.org)

## 4 Analysis of Magnesium Parts Manufacturing

### 4.1 Magnesium specific Design for Transport Applications

Magnesium has been used in transport applications for decades. During the 1970s, its use in the automotive industry reached its peak, as the drive train of the VW beetle was made from magnesium. The drive train and the interior are the main field of application in case of passenger vehicles. An overview of magnesium applications for road transport and aviation as well as a detailed analysis of engineering requirements is given in Friedrich and Mordike (2006).

Due to its physical properties, the use of magnesium offers various advantages. Main benefits are the low density and the very good castability. This allows an efficient production of lightweight components. The mechanical properties of magnesium allow the design of parts with thin wall thickness. Additionally, the component design can be optimized by incorporating ribs, cross sections, or other features. To fully use the potential of magnesium, an integrated approach of optimization of component shape according to its mechanical requirements, magnesium processing and machining tool design has to be found. Furthermore, recent research activities focus on the development of advanced magnesium alloys with improved properties (e.g. ductility and energy absorption) in order to minimize disadvantages of this material (e.g. strength to ductility ratio, corrosion behavior).

In the following, the main aspects of magnesium alloys for transport applications as well as the production of alloys and its environmental assessment are presented. Furthermore, two examples for magnesium components are analyzed. Firstly, the production of a steering wheel for passenger cars via die casting is evaluated. Secondly, an example for the use of magnesium in aviation is presented. The analyzed door parts for aircrafts are produced via sand casting.

### 4.2 Goal and Scope Definition for Parts Manufacturing

#### Goal

The analysis of magnesium alloying, die casting and sand casting are part of the analysis of magnesium processing. The focus is to provide magnesium specific process data and the analysis of technological options for improvements. Two exemplary magnesium applications are analyzed: a steering wheel frame used in a passenger car and door parts used in an aircraft. The door parts are a gearbox and a seal closer for each of top and bottom of an aircraft door (so together its three single parts). Both examples represent components that are currently in use in automotive and aviation applications. The use phase of the parts is analyzed in part II of this report. As the use is compared to equal products made from aluminium, the production of the aluminium components has been modeled as well. In this chapter, however, we focus on the magnesium processing.

The alloy production is treated as separate process step in order to assess the relevance of raw materials. In practice, some companies purchase raw magnesium and produce alloys in a separate

process. Alternatively, the alloys can be created directly at the magnesium production site as last process step of magnesium primary production.

The processes are specifically related to the parts which are evaluated. Some data like the energy consumption of the processes and the use of cover gases can be used for similar products as well. Other parameters like the amount of swarf are product specific and the use of this data is limited to the evaluation of a steering wheel or door parts of an aircraft, respectively.

### **Data collection and data quality**

In case of the model for magnesium die casting, data for a representative casting plant are used for calculation of the energy and cover gas consumption. A survey among die casting experts has been used to determine the figures on production waste and the standard scenario in terms of representative cover gas and technology for this process. The sand casting data is based on industry data of the component manufacturer for the part specific parameters. The energy consumption of this process is average industry data. The data for the amount of cover gas used is calculated according to data from EPA (2004) which is based on measurements in two die casting facilities. There is no average industry data on the consumption of cover gases available. Both processes represent the current production conditions for the part examples analyzed in this study.

In case of alloy production, the energy consumption is estimated by the advisory board of the study. For the comparison of magnesium and aluminium components in part II of the report, this figure is not relevant as we assume the alloying to be the last step of magnesium primary production.

### **System boundaries, background data and cut-offs**

The assessment of magnesium processing is a gate-to-gate analysis. That is that the production of magnesium alloy is not included in the assessment of die and sand casting. The analysis of alloy production is limited to the assessment of alloying elements and further material and energy consumption without the primary magnesium metal as this is evaluated in chapter 2 of this report. Upstream processes for energy and material supply are included. These upstream processes are taken from the ecoinvent database 2.2.

The geographical scope of magnesium processing is Europe. Data on energy consumption are based on German industry conditions, while for the energy supply we refer to the UCTE region. The cover gas consumption is based on data from North America, but it is not expected that consumption varies notable from region to region. For the information on typical types of cover gas used, we surveyed magnesium die cast experts in Germany.

There are no general cut-off rules applied. The alloying elements for magnesium alloys are restricted to the addition of the two major elements as other elements usually are included in these major elements as impurities.

## Allocation

There are no multifunctional processes directly involved in the models of magnesium processing. Regarding potential multi-output processes in the upstream process change, like for instance the heavy fuel oil production, the allocation procedure given in the ecoinvent database has been applied without changes.

## Functional unit and reference flow

The functional units of the product systems are the production process of a magnesium steering wheel frame made from AM50 for the use in a passenger car and the production process of three parts made from AZ91E for the use in an aircraft door (gearbox and two seal closers). The weights of the parts analysed in this study are as follows:

- steering wheel:
  - magnesium (AM50): 0.55 kg
  - aluminium (AlMg3): 0.74 kg
- aircraft parts:
  - magnesium (AZ91): 6.63 kg
  - aluminium (A356): 8.50 kg

In both cases, the weight of the component is the reference flow used in the energy and material flow model. For the models of aluminium parts, the weight represents components with equal functionality.

The alloy product is calculated for the amount of AM50 alloy needed to produce the steering wheel frame (0.58 kg) and the amount of AZ91E needed to produce the door parts (15.4 kg), respectively. The analysis of alloy production in this chapter shows the results mainly for the AM50 alloy.

## 4.3 Magnesium Alloys

### 4.3.1 Alloys for Transport Applications

Nearly all magnesium used in industrial application is die cast. There are only small amounts of sand cast or chill cast as well as wrought magnesium application. Room temperature application play an important role for magnesium die casting, therefore AZ- and AM-alloys are the common alloys in use. They show good room temperature strength and ductility as well as corrosion resistance and machinability. AZ alloys show a little more strength (AZ91) and AM-alloys more ductility (AM50, AM60). In both systems manganese is added for improving corrosion resistance. Parts like clutch housings, steering wheels and steering columns, brackets, seat frames and instrument panels are made of AZ- and AM alloys. Both alloy system lose strength and creep resistance when application temperature rises to 130°C and more due to the Mg-Al beta phase

Mg<sub>17</sub>Al<sub>12</sub>. This phase has a melting temperature of 437°C and starts to weaken at elevated temperatures.

For use at elevated temperatures commercial alloy systems containing silicon (AS-alloys) and rare earth elements (AE-alloys) have been developed. AS41 has creep strength higher than AZ91 and can be used up to 175°C. Mg<sub>2</sub>Si phase precipitates during solidification and stabilizes the microstructure at elevated temperatures. Crankcases and several other Volkswagen parts were cast from AS-alloys. A modified AS31 is used for the 7GTronic Gearbox housing from Daimler [Barth2004].

A further improvement in creep resistance show alloys containing rare earth elements besides aluminium (AE42, AE44). Stable Al-RE precipitates hinder dislocation movement and the amount of free aluminium is reduced, which avoids precipitation of Mg-Al beta phase. AE as well as AS alloys are more difficult to die cast, so the range of application is limited. Additionally, a supply shortfall of rare earth elements, which are primarily produced in China, limits their use, as well.

Noranda developed magnesium alloys for die casting with good creep resistance by adding strontium. The AJ-system containing 4-6 wt.-% aluminium and 1-2 wt.-% strontium (AJ52, AJ62) is used for example in the BMW six-cylinder engine housing and crankcase.

Magnesium alloys of WE- and ZE series show a further significant improvement in creep resistance and high temperature strength, but are not die castable. Sand casting or gravity die casting is used and huge parts can be produced. These alloys are in use for helicopter gear box housings and other huge parts with relatively low number of produced units.

Due to its energy consumptive primary production, recycling of magnesium alloys was of interest at all times. At the moment recycling takes place in house in die casting industry due to the fact, that about 30-50% of a die casting shot is not part of the final product. Ingate systems, runner, sprues and gates are cut off after the casting and can be remelted easily because they are of one alloy (Fechner, Hort et al. 2009).

Due to the increasing amount of magnesium used in the last years, it is expected to have an upcoming quantity of 27,000 metric tons of magnesium alloys from End of Live Vehicles (ELV) in 2017 (Scharf, Blawert et al. 2003). This material will be an outcome of shredder processes. Cars as well as electronic equipment will be shredded and subsequently the different materials will be separated by magnetic and eddy current processes. A light metal fraction containing aluminium and magnesium alloys is separated. Usually now from this material aluminium alloys are produced.

For the recycling process the sensitivity against impurities of iron, copper and nickel is important. These elements strongly influence the corrosion rate already in low concentration. For separation of different post-consumer materials scrap classes were introduced which subdivide the materials concerning their alloying elements, impurities coating, paintings, lubricants, dross from casting furnaces etc.

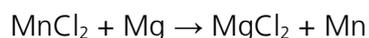
At the moment there are two different processes used for recycling magnesium alloys. One distinguishes between recycling with and without fluxes (Fechner, Hort et al. 2009).

Recycling with fluxes uses  $\text{MgCl}_2$ ,  $\text{KCl}$ ,  $\text{NaCl}$  as well as  $\text{CaF}_2$ ,  $\text{MgF}_2$  and  $\text{MgO}$ . These fluxes have a melting temperature lower than the magnesium alloy. A small amount of the molten fluxes always remains on the surface of the melt and therefore no cover gas is needed to prevent oxidation during the process. During the recycling process the fluxes pick up oxides from the melt. The higher the amount of oxides, the more flux salts are needed for the process. The mixture of melt and liquid flux has to be mixed all the time to ensure that the flux comes into contact with all oxides in the magnesium alloy melt. At the end of the process the mixture has to be settled for 10-15 minutes to assure that the oxide-flux-mixture sinks to the bottom of the mould. The process with fluxes cannot be used for magnesium alloys containing calcium, strontium and rare earth elements because their affinity to chlorine is higher compared to magnesium. During the process  $\text{MgCl}_2$  would be decomposed and calcium, strontium and the rare earths elements would be removed from the melt (Fechner, Hort et al. 2009).

Flux-free recycling is usually done in-house by die casting companies. It is possible only with material, which is widely free of oxides. This is class 1 scrap of only one alloy, directly taken from die casting processes. Therefore the flux-free recycling process is not competing with the flux recycling, because the materials are different (Fechner, Hort et al. 2009). A study performed by Meridian Magnesium together with Norsk-Hydro showed that the quality of recycled material equals the quality of the primary material in terms of corrosion resistance and mechanical properties (Berkmortel, Wang et al. 2000). Before melting the alloys, materials are preheated to  $350^\circ\text{C}$  in order to ensure the decomposition of  $\text{Mg}(\text{OH})_2$  and vaporize free water. It is recommended to use two furnaces for the flux-free process as well as for the flux-recycling: one for the melting and cleaning and one for the die casting. In the first cleaning furnace periodically re-movement of dross and oxides from the surface and the bottom is done. From the mid area between surface and bottom, the melt is transported into the second furnace for die casting.

### 4.3.2 Alloy Production and Life Cycle Inventory

Alloying takes place by adding metal elements or reducible compounds. In case of aluminium and zinc the pure metals are added to the magnesium melt and stirred until the additions dissolve. Manganese is added as  $\text{MnCl}_2$  usually. The melt is heated and the melt surface is cleaned before  $\text{MnCl}_2$  powder is distributed on the surface. The following reaction takes place:



The  $\text{MnCl}_2$  is reduced by the molten magnesium and the manganese metal liberated dissolves as the melt is stirred.

For the component examples in this study, two different alloys are considered (Table 1). The typical alloy for a magnesium steering wheel is AM 50. For the aircraft parts, AZ91E is used. The alloys consist of different alloy elements which are added into the magnesium melt. This melt has to be protected from oxidation by using specific cover gases. Furthermore, energy is needed for heating the furnace and the materials transported between production sites.

The composition of AM50 is taken from Kielbus, Rzychon et al. (2006). In the material and energy flow model, only aluminium and manganese are added as alloying elements. In case of aluminium, only primary metal is used. All other alloying elements come in as impurities.

The energy needed for alloy production is estimated to be 1 kWh per kg which includes the remelting of pure magnesium. As protective gas, three alternatives can be used: either a mixture of SF<sub>6</sub> / air, SO<sub>2</sub> / air or R134 / air. The data for the use of cover gas are equal to the data used in the die casting process (see chapter 4.4.2). The distances for material transport are default values for an average transport of raw materials (not based on statistical data).

**Table 11: Model parameters for alloy production (AM50 and AZ91E)**

<b>type of input</b>	<b>amount unit</b>
<b>AM50</b>	
aluminium content	4.9 wt-%
manganese content	0.45 wt-%
zinc content	0.2 wt-%
silicon content	0.05 wt-%
nickel content	0.01 wt-%
copper content	0.008 wt-%
iron content	0.004 wt-%
beryllium content	0.001 wt-%
<b>AZ91E</b>	
aluminium content	9.0 wt-%
zinc content	0.7 wt-%
manganese content	0.26 wt-%
electricity	1 kWh/kg alloy
<b>Cover gas</b>	
- SF6	1.1 kg/t alloy
- SO2	2.2 kg/t alloy
- R134a	0.01 kg/t alloy
- CO2	6.4 kg/t alloy
transport (lorry)	100 km
transport (rail)	100 km

The reference flow for the model of alloy production is the amount of alloy needed to produce one component.

The alloy production usually takes place at the site of primary magnesium production. Primary electrolytic producers prepare alloys directly from crude magnesium. In case of the Pidgeon process, the alloy is either produced directly or alloy producers use magnesium crowns for their process. Thus, when analysing the entire life cycle of magnesium as described in part II of this report, the material and energy use for alloy production is included in the final steps of magnesium production. This means that no extra energy and cover gases are needed for the alloy production. Only the alloying elements need to be provided.

## **4.4 Magnesium Processing**

### **4.4.1 Routes for Component Manufacturing**

#### **Die Casting**

More than 90% of all magnesium alloys are processed via die casting. This number gives the importance of the process as well as the die cast alloys. The production rates are usually higher compared to aluminium alloys, because solidification and chilling is faster due to the lower heat content of magnesium alloys. Another advantage of magnesium die casting compared to aluminium die casting is the longer life-time of tools. Different to aluminium the solubility of magnesium in tool-steel is close to zero, which reduces surface reaction significantly. That makes melting and handling easier and cheaper and life-time of dies and tools can be doubled in some cases compared to aluminium die casting (Luo, Renaud et al. 1995). Magnesium alloys can be cast in the hot- or cold-chamber die cast process.

The cold-chamber die casting process is characterized by a separation of casting facility and melting furnace. Therefore the melt temperature has to be higher compared to the hot-chamber process. Due to this the casting unit is not exposed to the melting temperature and it is possible to achieve closing forces up to 50,000 kN. Usually alloys like AE42, AS21 or AJ62 need higher temperatures during casting due to their higher solidus temperature and a smaller freezing range. In hot-chamber die casting mainly alloys like AZ91 and AM50/AM60 are processed. The casting facility and the melting furnace are connected because the dosing system is placed in the melt. The weight of parts processed in cold-chamber die casting can be much higher compared to hot-chamber die casting but the cycle times are longer. An advantage of hot-chamber die casting is the lower wall thickness which can be cast.

#### **Sand Casting**

Usually aluminium-free alloys like WE43, QE22, EZ33, ZE41 or Elektron21 are used for sand casting. Zirconium is added for grain refinement which additionally improves good creep resistance of these alloys. Gearbox housings of helicopters and other low volume, heat resistant parts are cast via sand casting. Compared to die casting, sand casting offers lower cost tooling and the ability to produce large or extremely complicated shapes, including oil passageways that cannot be produced in die castings.

#### **Extrusion**

Already since beginning of the last century magnesium alloys are processed by extrusion. Long profiles with uniform cross section can be extruded and the process is already described in Beck (1939). Three different extrusion principles are distinguished which is direct, indirect and hydrostatic extrusion. In all cases a cast billet is put into a container and subsequently pressed through a die which is the negative of the profile. Die preparation and lubricant as well as temperature, extrusion ratio and extrusion speed are the main parameters, which can be varied. Magnesium alloys are typically extruded in a temperature range between 300°C and 450°C. In the direct extrusion process the preheated cast billet is pressed by an extrusion tool through the

fixed die, whereas the indirect process the die is pressed into the fixed billet. The flow of material is more uniform in the latter case because no friction between billet and container takes place. In the hydrostatic extrusion process the billet is put into a container as well but is surrounded by a fluid medium on which pressure is applied. The applied hydrostatic pressure forces the billet through the die without friction on one of the die walls. The number of alloys suitable for extrusion is small, usually AZ31, ZE10, ZEK100 or WE-alloys are used. During extrusion processes grain size is reduced significantly but due to the high temperatures, which even can increase during process due to friction, recrystallization can take place (Bohlen, Letzig et al. 2007).

Further progress of this technology is expected in the future. Due to a better understanding of magnesium alloys, the forming process can be optimized. Especially the use of twin roll cast strips is seen as possible input for the magnesium forming process. The further processing of magnesium sheets which includes deep drawing, joining and coating is also subject to research and development activities (Bohlen, Letzig et al. 2007; Dieringa, Bohlen et al. 2007).

A study on the energy efficiency of extrusion moulding showed that the energy consumption of extrusion is about 0.6 kWh per kg extruded profile. This would lead to CO<sub>2eq</sub> emissions of about 11.1 per kg extruded profile based on the German electricity mix. The environmental impacts of die casting and sand casting are presented in detail in the following chapters.

#### 4.4.2 Life Cycle Inventory for Magnesium Steering Wheel

The model for manufacturing a steering wheel which is used in a car refers to the steering wheel frame as functional unit (referred as "steering wheel" in the following) (Figure 22). The weight of the steering wheel from magnesium is 0.55 kg and the alloy used is AM50. A second model has been developed in order to compare the manufacturing of the magnesium steering wheel with one made from aluminium. The weight of the aluminium steering wheel is 0.74 kg.

Steering wheels are produced via die casting. As explained in chapter 4.4.1, there are two process paths relevant in the die casting industry: cold-chamber and hot-chamber operation. Data for material and energy consumption in literature usually refer to cold-chamber die casting.

Compared to this technology, the hot-chamber die casting is expected to have slightly higher energy consumption due to the preheating of the moulds. This applies both for magnesium and aluminium, as material and shape of the moulds are equal. Due to the data available for die casting, the models for the production of the steering wheel do not distinguish between cold- and hot-chamber technologies. The input data for material and energy consumption of the magnesium die casting process are listed in Table 12.



Image source: Kern GmbH ([http://www.kern-mg.de/de/Gussbeispiele/site\\_\\_174/](http://www.kern-mg.de/de/Gussbeispiele/site__174/))

**Figure 22: Magnesium steering wheel frame**

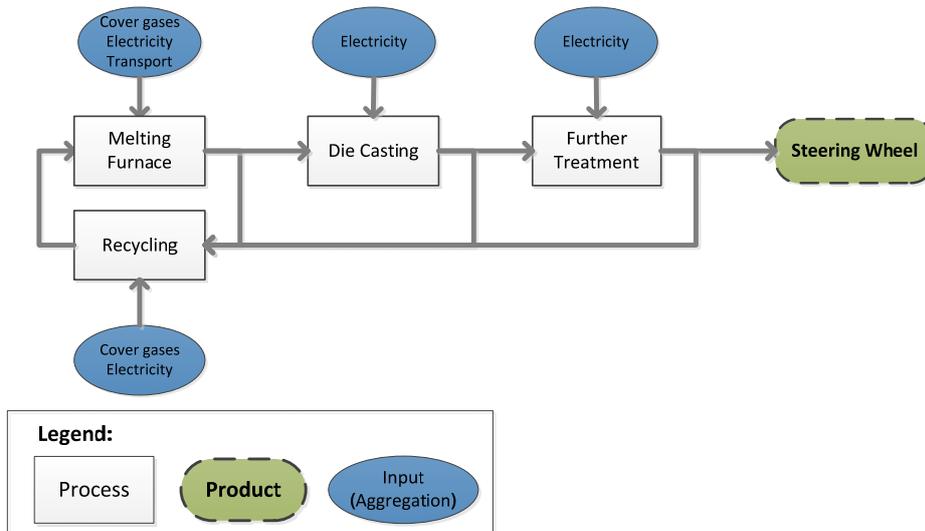


Figure 23: Inputs and process steps of magnesium die casting

Table 12: Input data for magnesium die casting process

type of input	amount	unit	note
<b>Cover gas</b>			
- SF6	1.1	kg/t alloy	
- SO2	2.2	kg/t alloy	
- R134a	0.01	kg/t alloy	
- CO2	6.4	kg/t alloy	
<b>Furnace</b>			
- natural gas (furnace)	0.82	kWh/kg alloy	
- electricity (furnace)	0.55	kWh/kg alloy	
electricity (die casting machine incl. peripheral equipment)	0.88	kWh/kg alloy	
transport (lorry)	100	km	default value
transport (rail)	100	km	default value

The furnaces for melting the magnesium can be operated either by gas or electricity. Thus there is either 0.82 kWh of natural gas or 0.55 kWh of electricity needed for the process. To prevent oxidation, the use of a cover gas is necessary. Three different alternative gas types are analyzed in this study:

- SF<sub>6</sub> / air mixture
- SO<sub>2</sub> / air mixture
- R134a / CO<sub>2</sub> mixture

In literature, the amount of SF<sub>6</sub> varies considerable. Classen, Althaus et al. (2007) report amounts of 0.25 to 10 kg per t Mg. The consumption of cover gases shown in

Table 12 is based on EPA (2004), where empirical data on the consumption of cover gas in magnesium die casting are published. These data refer to the U.S. industry, but we assume that the differences to industries in other regions are negligible. EPA (2004) reports emissions from die casting. In the steering wheel production model, we assume that the input amount is equal to the emissions of cover gases. The method for calculating the amounts of cover gas needed is shown in Annex II).

Data for the energy consumption of gas and electricity operated furnaces are taken from Dalquist and Gutowski (2004) for gas operated furnaces and from IfG (2008) for electric operated furnaces. The data represent an energy efficient state-of-the-art die casting process. A survey among die casting companies and experts showed that electric operated furnaces are the most common in die casting industry.

A further input parameter for the die casting process is the share of production scrap. This includes sprues, burring waste, swarf and defective parts. The amount of production scrap depends strongly on the parts produced and thus, data in literature vary considerable. Zhang and Dupont (2007) state that in magnesium processing about 50 % of the consumed alloy ends up in the final product. The result from the survey show that this value varies from 50 to 90 % (see Annex III). The share of defective parts is comparatively low. For a specific, equal product, the amount of production waste for magnesium and aluminium processing is equal. Though data in literature appear to show that aluminium offers lower amounts of production scrap, this does not apply for the comparison of one product made from either magnesium or aluminium. In case of a steering wheel, the typical amount of production scrap is 45 %.

Regarding the treatment of the production scrap, the magnesium processing usually requires a separate recycling process. Either the scrap is recycled in-house in a separate furnace or brought to an external recycling site before entering the die casting process again. For the die casting model, the furnace for the recycling of magnesium production scrap is calculated with the same specification as listed in Table 12.

For the transport of raw and operating materials, a default distance of 100 km is used in the model.

In a further treatment step, the component is deburred and cleaned. For this process, 0.33 kWh of electricity per kg product are needed (Dalquist and Gutowski 2004).

Apart from the production of R134a (McCulloch and Lindley 2003), the data for upstream processes are taken from the ecoinvent database v2.2.

A second model for the production of a steering wheel made from aluminium has been developed. Energy consumption and transport per kg alloy are the same as for the magnesium die cast and further treatment processes as both materials have a similar melting point. As melted aluminium does not need any protection agents, there is no cover gas needed for the process. And in contrast to the recycling of magnesium production scrap, the aluminium scrap is re-used directly for die casting without a separate recycling process.

### 4.4.3 Life Cycle Inventory for Magnesium Aircraft Parts

For the magnesium use in aviation, three components that are part of an aircraft door serve as example (Figure 24). The parts are a gearbox and a seal closer for each of top and bottom of an aircraft door. The parts are produced via sand casting. The functional unit of the models developed for magnesium and aluminium is the production of all three parts together. The weight of the door parts amounts to 6.63 kg. The aluminium part which is used for component comparison weights 8.5 kg which is a weight difference of 22 %. The surface of the parts and the amount of production scrap are the same for both metals. The amount of alloy needed for the component production is 15.4 kg. That results from the amount of melt residue of the sand casting which is recycled and reused. This material amounts to 60 kg of which 11 % is lost and end up in the waste slag. The alloy needed for the product prior to further processing as well as the material losses have to be added to the sand casting process as new alloy.



Figure 24: Examples for magnesium parts in aircraft doors

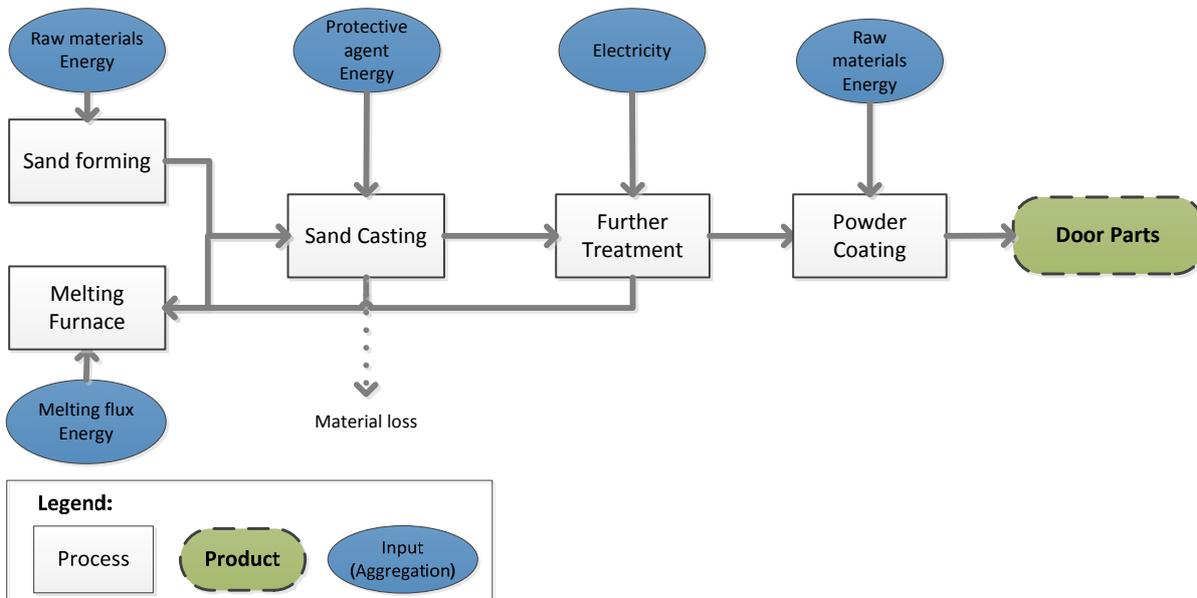


Figure 25: Inputs and process steps of sand casting model

**Table 13: Component specifications for aircraft parts**

	<b>Mg sand casting</b>	<b>Al sand casting</b>
	amount unit	amount unit
<b>Product data</b>		
door parts (aircraft)	6.63 kg	8.5 kg
door parts (aircraft)	1.72 m <sup>2</sup>	1.72 m <sup>2</sup>
swarf, gates, etc.	23.7 %	23.7 %
<i>Alloy</i>		
AZ91E: aluminium	9.0 wt-%	not to apply
AZ91E: zinc	0.7 wt-%	not to apply
AZ91E: manganese	0.26 wt-%	not to apply
A356: silicon	not to apply	7.0 wt-%

Figure 25 depicts the process steps of the sand casting model. Unlike in the die casting process, the moulds have to be formed exclusively for the casting of each part. After the sand casting step itself, the parts have to be cut into shape and powder coated in a further treatment step. The process parameters used are listed in Table 14.

Sand moulds are produced when patterns are filled with a mixture of artificial or natural sand, binding materials (most typically phenolic urethane resins) and an inhibitor to prevent the magnesium from reacting with the sand. Potassium tetrafluoroborate (KBF<sub>4</sub>) is needed as protective agent in the magnesium processing. The sand mixture is compressed in a forming machine for which the energy consumption is taken from IfG (2008). The relation forming material : magnesium is 20:1 according to Podobed (2003). Data for sand recovery and energy consumption for recovery are inserted as given in IfG (2008).

Prior to pouring, the sand mould is filled with either a gas such as argon to displace oxygen or an inhibited gas that reduces the reactivity of the metal in the mould. In our model, we assume that the sand mould is filled with a mixture of SO<sub>2</sub> and air. In the sand cast process itself, the alloy is melted and poured into the sand mould. After cooling, the mould is destroyed and the cast part is treated further. Most of the excess gating and risering taken from the sand mould is processed directly back into future melts. For the preparation of the magnesium melt, a protective flux is used instead of cover gases. After the casting process step, the parts are cut into shape. The electricity consumption for this process is taken from IfG (2008). The calculation of the final powder coating is based on the surface of the parts. This process is estimated using a similar process from the ecoinvent database 2.2.

The upstream processes for material and energy use for this model are also taken from the ecoinvent database 2.2.

**Table 14: Input Parameters for magnesium and aluminium sand casting process**

	<b>Mg sand casting</b> amount unit	<b>Al sand casting</b> amount Unit
<b>Sand forming plant</b>		
<i>Composition sand mould</i>		
sand	97.9 %	98.9 %
phenolic resin	1.1 %	1.1 %
KBF4	1 %	not to apply
<i>Energy consumption moulding machine</i>		
electricity	0.0165 kWh/kg sand mould	0.0165 kWh/kg sand mould
heating oil	0.0004 kg/kg sand mould	0.0004 kg/kg sand mould
natural gas	0.0065 kWh/kg sand mould	0.0065 kWh/kg sand mould
<i>Mould material</i>		
share conditioned sand	20.0 kg/kg unfinished casting	16.4 kg/kg unfinished casting
energy sand conditioning	85 %	85 %
	41 kWh/t sand	41 kWh/t sand
<b>Sand casting</b>		
SO <sub>2</sub>	2.2 kg/t alloy	not to apply
Flux	0.01 kg/t alloy	0.001 kg/t alloy
- KCl share	55 %	50 %
- MgCl <sub>2</sub> share	40 %	not to apply
- NaCl share	not to apply	45 %
- CaF <sub>2</sub> share	5 %	5 %
Natural gas (gas furnace)	0.82 kWh/kg alloy	0.82 kWh/kg alloy
transport (lorry)	100 km	100 km
transport (rail)	100 km	100 km
<b>Further treatment</b>		
electricity	1.07 kWh/kg end product	1.07 kWh/kg end product

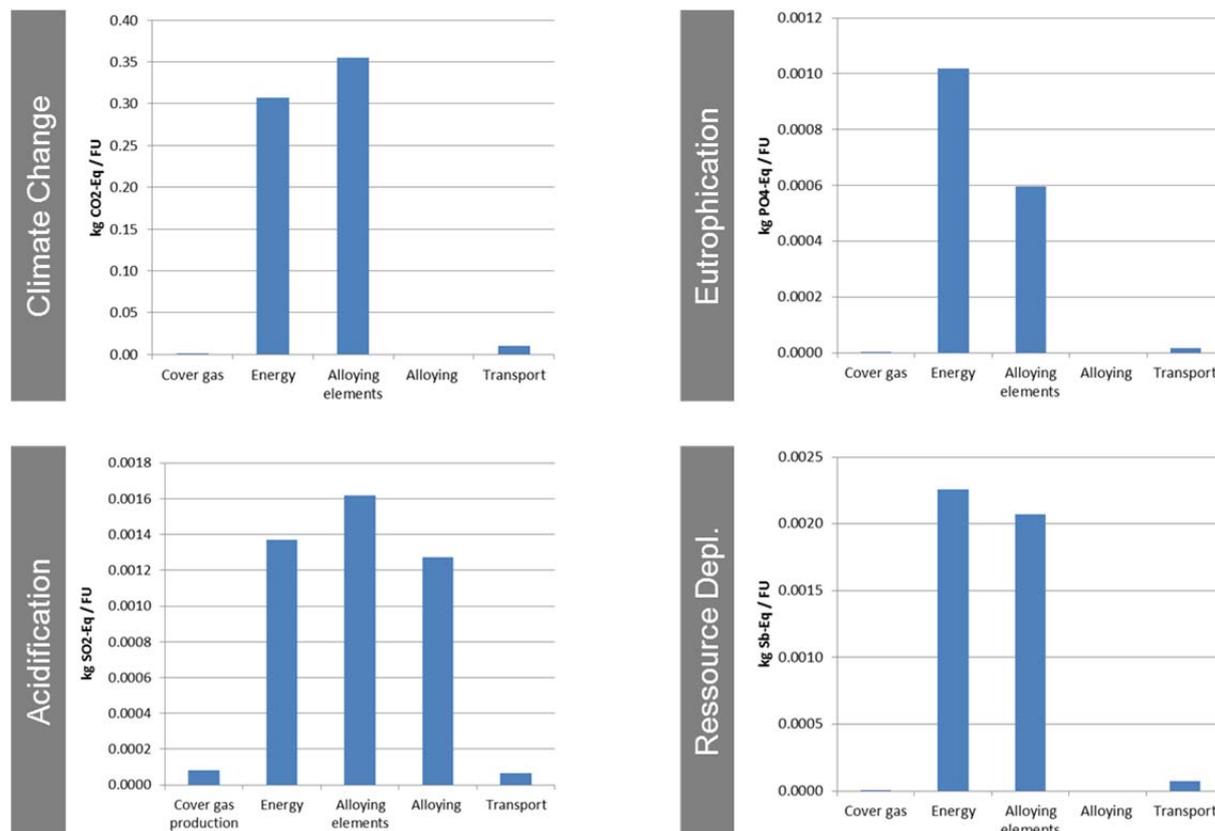
A second model for the production of sand casting parts from aluminium has been developed. The model is based on the input data from the magnesium sand casting model. In contrast to the magnesium model, no boric acid is needed for the sand mould and protection gas is needed for the mould. The composition and consumption for the melting flux differs slightly.

## 4.5 Environmental Indicators for Production of Components

### 4.5.1 Results for Alloy Production

The results of the impact assessment for alloy production are shown in Figure 26. The impacts are shown for the alloy production using SO<sub>2</sub> as cover gas as this is seen as standard cover gas in magnesium processing industry. In consequence, the cover gas has considerable influence on the acidification potential in the alloying process step. Generally, the energy supply and the

production of primary aluminium and manganese as alloying elements show highest emissions and resource consumptions. The use of primary aluminum for alloy production contributes with 0.34 kg CO<sub>2eq</sub> to the overall emissions of about 0.35 kg CO<sub>2eq</sub> from the alloying elements upstream process.



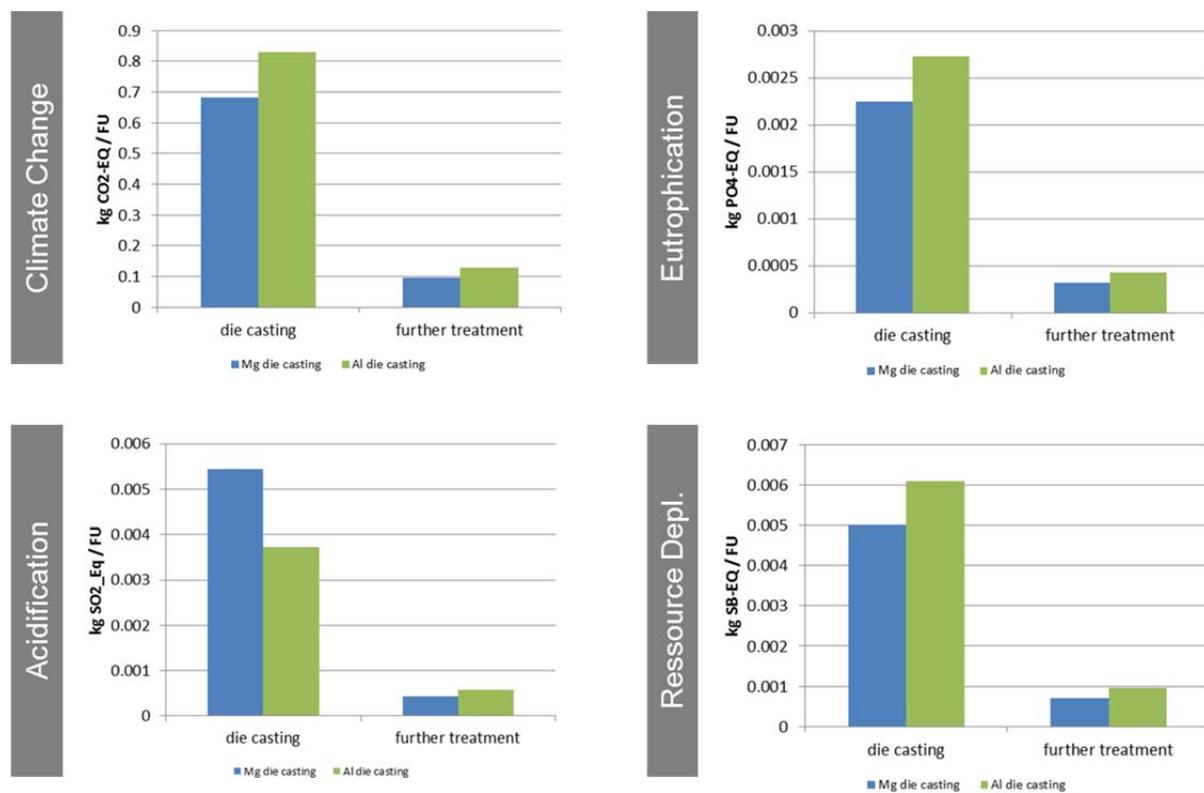
**Figure 26: Results of impact assessment for magnesium alloy production**

The main influencing factors also apply for the production of the AZ91E alloy which is used for the aircraft parts. In addition to manganese, zinc is added as alloying element. The overall greenhouse gas emission for the production of 8.6 kg alloy needed for the door parts is 25.6 kg.

### 4.5.2 Results for Magnesium Steering Wheel

For the evaluation of the production of the steering wheel, a standard scenario for die casting is defined. This scenario includes a rate of production waste of 45 %, the use of electric furnaces for die casting and the use of SO<sub>2</sub> as cover gas for the magnesium part. These parameters are seen as most representative for an exemplary steering wheel production. The system boundary for input materials is set at the supply of magnesium and aluminium alloy. The production of alloy and the related upstream processes are not included in the impact assessment. The results

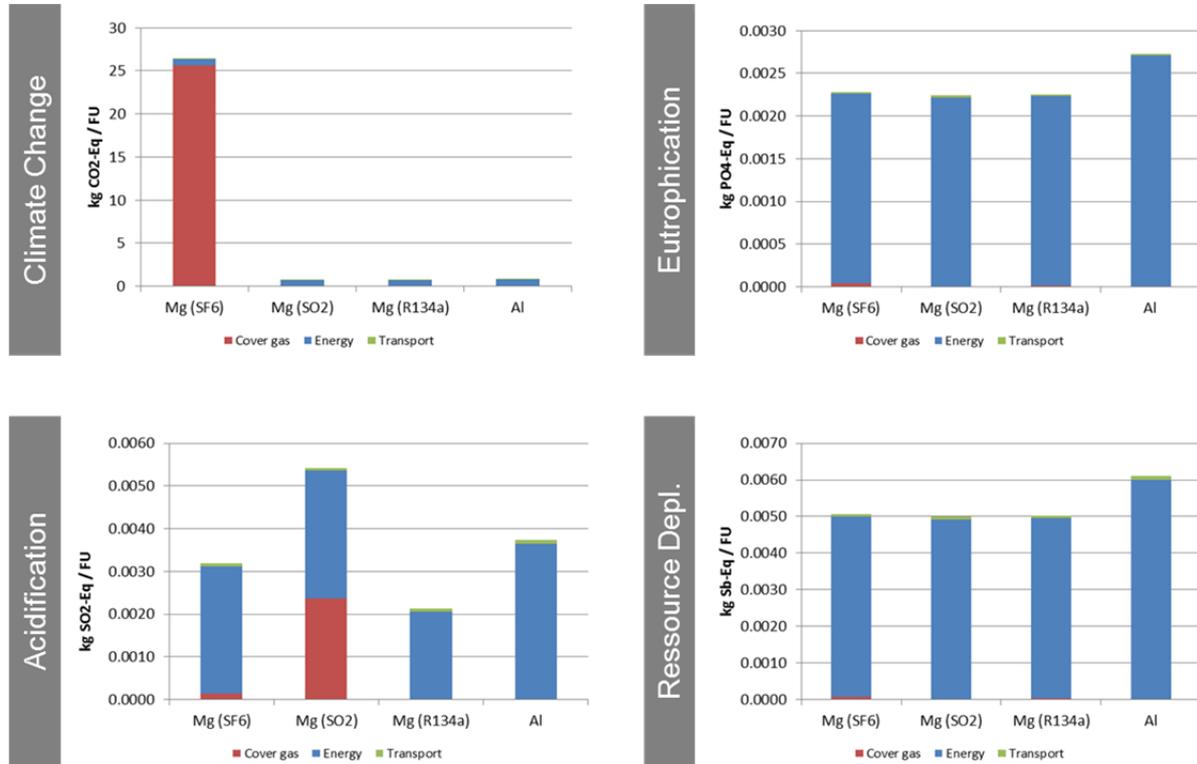
presented in this chapter concentrate on a gate-to-gate analysis of die casting and further treatment and the related upstream processes for energy and material supply (excluding alloy). The impact assessment of the die casting process shows that in general, the die casting step itself has higher environmental impacts than the further treatment of the parts (Figure 27). In both process steps, the magnesium steering wheel has lower impacts compared to the aluminium part. Only for the acidification category, the use of SO<sub>2</sub> as cover gas leads to comparatively high emissions. As the functional unit of the models is one steering wheel, the results include that for the magnesium component less material has to be processed. This implies also a lower energy consumption for the process.



**Figure 27: Results of impact assessment for steering wheel production (gate-to-gate)**

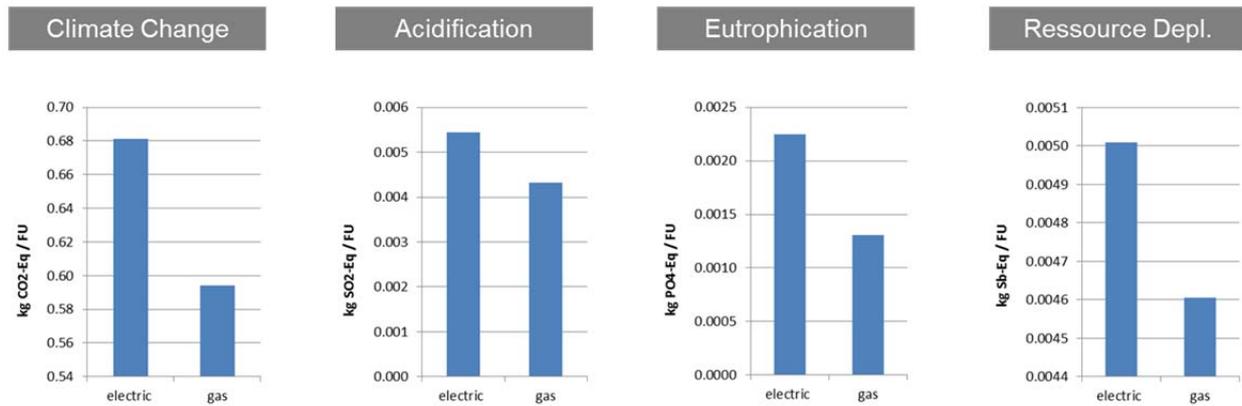
The contribution of cover gas use, energy consumption and transport to the gate-to-gate result is depicted in Figure 28. For the magnesium steering wheel, scenarios for the use of different cover gases are calculated. The climate change category clearly shows the impact of the potent greenhouse gas SF<sub>6</sub> which leads to emissions of 26.3 kg CO<sub>2eq</sub> per steering wheel. The use of R134a, though being a comparatively potent greenhouse gas as well, results in greenhouse gas emissions of 0.7 kg CO<sub>2eq</sub> which is more or less in the same range as the SO<sub>2</sub> and aluminium scenarios. The acidification category is dominated by the use of SO<sub>2</sub> as cover gas. For eutrophication and resource depletion, the consumption of electricity is the dominant factor

which is independent from the type of cover gas used. The contribution of the transport processes is less important in all categories.



**Figure 28: Contribution of cover gas, energy and transport to the impact assessment of die casting process (gate-to-gate)**

The use of electric operated furnaces for die casting is seen as representative in today’s die casting industry. Due to economic and technical reasons, most companies use this type of furnace. Yet the use of gas operated furnaces has advantages from an environmental point of view. As shown in Figure 29, the use of furnaces operated with natural gas leads to lower impacts in all categories. Though energy consumption is higher for these furnaces, the overall efficiency of the energy process chain is better.



**Figure 29: Results for impact assessment of magnesium die casting process step for electric and gas operated furnace**

### 4.5.3 Results for Magnesium Door Panel

For the impact assessment of the production of aircraft parts, the functional unit is three parts of an aircraft door. The analysis is a gate-to-gate approach and includes the sand casting and further treatment without regarding the supply of magnesium and aluminium alloys.

Figure 28 shows the results for the impact assessment of the sand casting process. The total process is broken down into the contribution of the single process steps for both the magnesium parts and the aluminum parts. For the categories climate change and resource depletion, the production of magnesium parts has lower impacts than the production of aluminium parts. The potential impacts on eutrophication are in the same range.

In the magnesium model, the production of the sand moulds has considerable influence in all impact categories. The main impacts in this process result from the consumption of phenolic resin and KBF<sub>4</sub>. As for the production of the latter a general dataset on inorganic chemicals is used as approximation, the contribution of this chemical to the impact results is uncertain. In case of the category climate change, the cast process itself is the dominant process due to the consumption of fluxes and energy. Main influencing parameter in this process step is the high energy consumption. For the acidification potential, the use of SO<sub>2</sub> which is filled into the mould plays a major role for the magnesium parts.

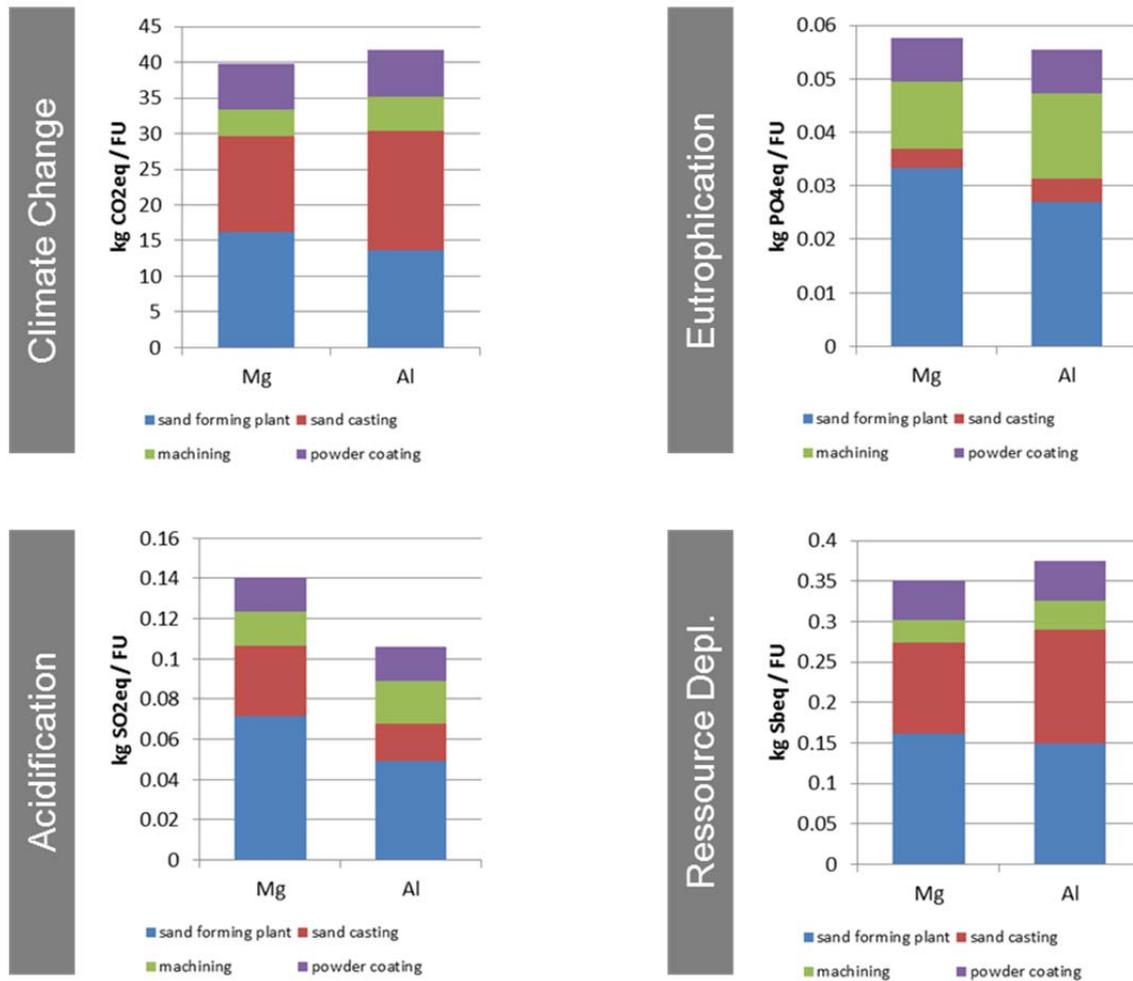


Figure 30: Contribution of single process steps to the impact assessment of sand casting process (gate-to-gate)

#### 4.5.4 Sensitivity Analysis

The dependencies of the results of impact assessment and the share of production scrap are shown in Figure 31. An increase of the material utilization fraction from 55 % to 90 % for the die casting of steering wheels leads to a reduction of about 30 % in all impact categories. Greenhouse gas emissions would fall from 0.68 to 0.48 kg CO<sub>2eq</sub> per steering wheel. The reduction of processing scrap and defective parts should be a major goal.

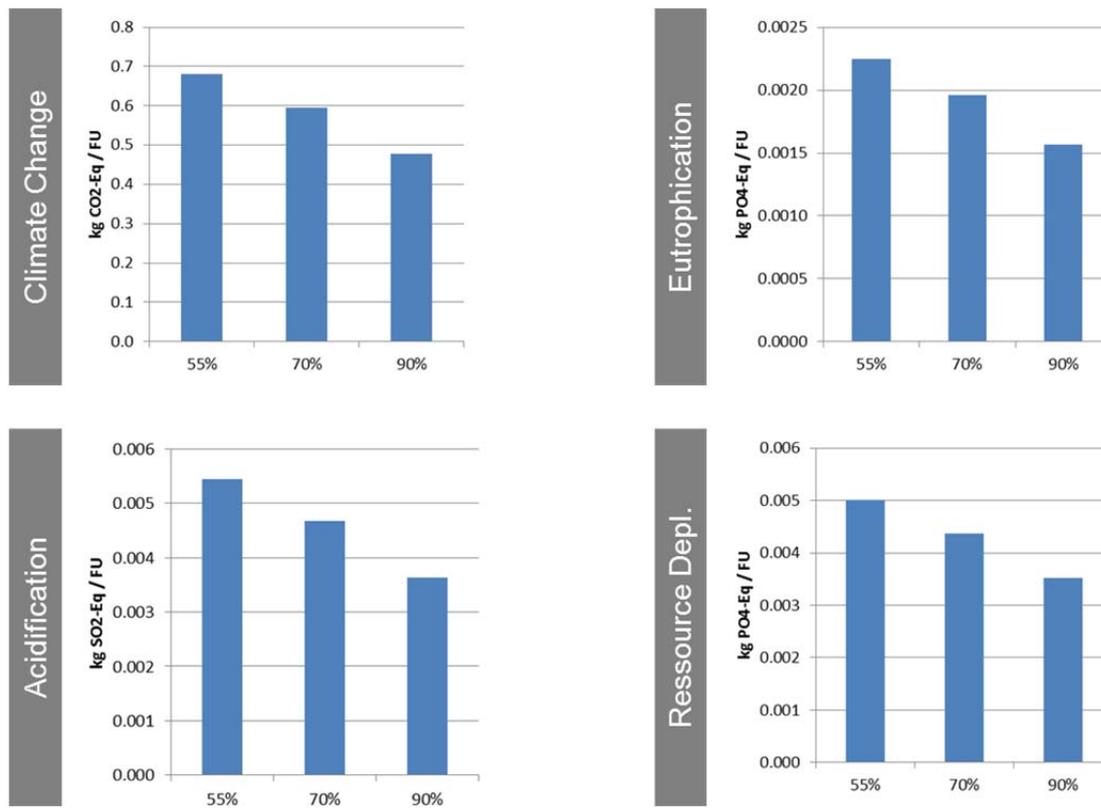


Figure 31: Results of impact assessment of magnesium die casting process for different shares of material utilization fraction

## 5 Analysis of End of Life and Recycling

### 5.1 Methodological Approach for Assessing Recycling Options

The fundamental idea of a life cycle assessment is the evaluation of a product from cradle to grave. Material cycles can develop and when a product is recycled, the end of the first life cycle leads to a new product system. For assessing such recycling paths, different approaches are described in ISO 14044 and literature (e.g. (Frischknecht 2010)).

In principle, two extreme approaches can be defined. In the so called *cut-off approach* the first product system includes neither burden nor benefits from the treatment of its EOL materials. Consequently, the material recycling and reprocessing process and all the corresponding environmental impacts are allocated to the secondary product. In the *avoided burden approach* the first product system includes the material recycling and reprocessing and gets a credit for the materials or services the secondary products substitute. There are different opinions on in which case to grant the credit for reducing the environmental impact: Only in combination with closed-loop recycling systems (Wötzel 2007) or generally if primary material is substituted equivalently in terms of material properties in a secondary product system (Frischknecht 2010).

In addition to these extremes, there are various approaches to allocate the environmental impacts of the recycling process to the products of the material's life cycle (Wötzel 2007; Klöpffer and Grahl 2009). Consequently there are also different methods of giving credits for substituting primary material. Just like the rules of allocation for multiple product systems, these methods are based on technical or economic criteria or on conventions agreed upon by LCA experts. A common practice is to allocate environmental impacts and credits in equal shares on both product systems (Klöpffer and Grahl 2009). Assumptions on recycling rate and credits for a product system influence the result of comparative product-related LCAs notably. This will be shown in Part II of this report where the use of magnesium is compared to aluminium.

The focus of this chapter is the end-of-life of components used in passenger vehicles. The basic ideas apply also for components used in aircrafts, but due to the amount of scrap, the treatment of road vehicles bears much more potential for a valuable reuse of magnesium than its use in aviation. Parts of contents are taken from Ehrenberger and Friedrich (2013).

### 5.2 Goal and Scope Definition for Magnesium End-of-Life

#### Goal

The evaluation of the end-of-life of magnesium parts in vehicles and the recycling aims to assess a representative recycling path for magnesium components in vehicles. We developed a model for the processing of end-of-life vehicles as well as for the reuse of magnesium. The further use of magnesium as alloying element for aluminium is analyzed as standard path for today's end-of-life of magnesium components. Additionally, we analyze the recovery of primary magnesium as alternative path. Further, we give an overview of recycling yields for magnesium.

### **Data collection and data quality**

The model on magnesium end-of-life is based on primary data for the recycling processes and on data from literature (esp. Wötzel (2007) for the end-of-life vehicle treatment). The figures on use of secondary magnesium and on recycling rates are based on data from one company. There is no average industry data available for the vehicle treatment and material sorting processes.

### **System boundaries, background data and cut-offs**

The analysis of the magnesium end-of-life is a gate-to-gate approach. The production and use of the components is not included in the model. The data is based on German sources, but it can be expected that the results are similar in EU countries. No general cut-off rules are applied. For upstream processes like electricity production, data from the ecoinvent database 2.2 are used.

### **Allocation**

The processes of the end-of-life vehicle treatment are allocated according to the mass of the component.

### **Functional unit and reference flow**

The functional unit of the end-of-life model is 1 kg of material which is available for reuse after passenger vehicle treatments and recycling. For the standard path of magnesium end-of-life, the reference flow is 1 kg of aluminium alloy (containing 3 % magnesium as alloying element). The reference flow for the alternative scenario is 1 kg refined magnesium.

## ***5.3 Recovery of Aluminium and Magnesium from End-of-Life Vehicles***

### **5.3.1 Legal Framework**

To examine a product in a life-cycle approach comprises also the assessment of the end-of-life related energy consumption and emissions. Assessing materials used in cars in terms of reuse and recycling is not only relevant in a life-cycle analysis approach but also driven by EU-legislation.

European Council - Directive 2000/53/EC on end-of-life vehicles specifies a minimum reuse and recycling rate of 80 weight-%, whereas at least 85 % have to be reused and recovered.<sup>8</sup> The recovery rate will be raised in 2015 to 95 weight-%, of which maximal 10 % may be energy recovery. Therefore, manufacturers are obligated to design vehicles that can be dismantled and / or recovered and recycled with reasonable effort at the end-of-life.

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<sup>8</sup> The term 'recovery' (in contrast to 'reuse' and 'recycling') refers to an energetic usage of materials.

Jody, Daniels et al. (2010) provides an overview of regulations on end-of-life vehicles throughout the world from which most of the following information is taken.

Canada has introduced regulation on ELV recycling on all political levels. In addition to that different industry associations have developed best practice guides for their members (Environment Québec, Ontario Automotive Recyclers Association).

Automotive recycling policies in China went into effect in 2010. The “Motor Vehicle Product Recovery Technology Policy” sets the minimum average weight per vehicle that has to be recycled or reused to 85% for all ELV products. The regulation initially tackled the recycling of engines, transmissions, electrical generators and a few other major parts. China is currently reviewing regulation after 2 million vehicles were improperly recycled in 2008.

Japan introduced the Automobile Recycling Act in 2002. This law has set ground for the monitoring of ELV recycling. Going into effect in 2005, the law requires car manufacturers to charge recycling fees from consumers provide dismantling manuals for their products and take responsibility for the process of recycling of ELVs. In addition to that manufacturers must take back their brand’s vehicles and properly collect and dispose shredder residue from scrap dealers. Owners of ELVs are obliged to dispose their vehicles at authorized recycling facilities.

Lacking the needed infrastructure has frozen the development of automobile dismantling and manufacturer take-back regulation in Russia.

South Korea has not yet developed a regulation on recycling ELVs. However, the “Vehicle Law” regulates the take-back and proper collection of ELVs. Existing recycling laws contain policies aiming at averting the usage of non-recyclable parts in vehicles (E.g. ecological design of vehicles)<sup>9</sup>.

The recovery of aluminium and magnesium from End-of-Life vehicles in the United States is not stringently regulated on federal level. On state level, many states do not consider regulation to be an effective means to encourage the recyclability of shredder residue. Therefore, a required ELV recycling system is not desired. However, California has started to re-examine the regulation for the recycling of shredding residue. ELV regulation in Connecticut, Maine, Minnesota, North Carolina, Oregon, Texas, and Washington are limited to certain electronic waste, mercury switches, waste oil, lead acid, batteries, and tires.

### 5.3.2 Processing of End-of-Life Vehicles

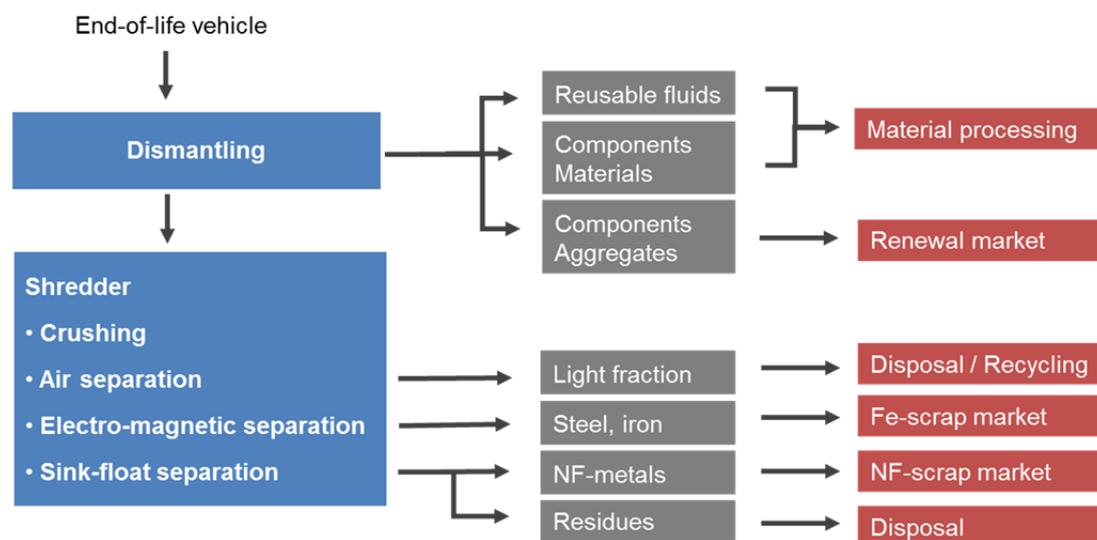
The processing of end-of-life vehicles consist of several steps (Figure 32). First, the vehicle is drained and specific parts are dismantled, e.g. batteries, tires and the catalyst. These components return to the market as used parts or are recycled in dedicated facilities. The complete drive train is sometimes removed from the vehicles, as this scrap yields high market price ((Diekmannshenke 2011), (Wolf 2000)). The drive train is then shredded as is the remaining car body. The

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<sup>9</sup>[http://www.brass.cf.ac.uk/projects/Sustainable\\_Mobility/towards-sustainable-mobility--ELV-and-Recycling.html](http://www.brass.cf.ac.uk/projects/Sustainable_Mobility/towards-sustainable-mobility--ELV-and-Recycling.html)

subsequent processes separate the materials from each other. Ferrous metals are removed by a magnetic separator. The remaining fractions are treated by different processes.

The light fraction, which consist of plastics, wood and glass, can be separated by air separation, non-ferrous (NF) metals by eddy flow separators. The NF-fraction is composed of a mix of aluminium, magnesium and heavy metals (mainly copper). As cars contain more aluminium than other NF-metals, the majority of this fraction is made up of aluminium. The NF-fraction can be separated in a float-sink plant. However, the majority of this NF-fraction is being shipped to Asia, and here mainly to China, where the fate of the materials is unclear. Gesing and Dubreuil (2008) report that the materials are processed by manual sorting. However, on-site research in China could not confirm this statement.



**Figure 32: Recycling process for end-of-life vehicles**

### 5.3.3 Recycling of Magnesium and Aluminium

The recycling of aluminium and magnesium from end-of-life vehicles is possible for both metals. Most of the available magnesium scraps stems from the magnesium die-casting industry. There is about 40,000 tons of die-cast scrap constantly in circulation. About 3,000 tons are unusable and end up as land-fill (Willekens 2012). The end-of-life magnesium die casting scrap exported from Europe is estimated to be 20,000 t / year (peak-year 40.000 t) (Willekens 2012).

In the case of easily removable attached parts at end-of-life vehicles, these can be removed at the beginning of the recycling process and purified for the according secondary market. But this is rarely undertaken, yet. Under the present circumstances aluminium is primarily recycled and put into market as secondary alloy. In the year 2009 the EU15 countries had a net amount of scrap aluminium of 830,000 t, from which 550,000 t were allotted to China. Technically, it would be

possible to separate magnesium and aluminium, for example with a float-sink system or via x-ray separation. The float-sink system separates materials of different densities with a suspension whose density is between the densities of the two materials. In the case of aluminium and magnesium, this is difficult, since thin and hollow aluminium parts are ending up in the magnesium fraction (Gesing and Dubreuil 2008). Sensor based systems, like the x-ray fluorescence analysis, can be used alternatively. Here, the material is distributed on a conveyor belt, irradiated via x-ray source, and the elemental composition is analysed with detectors. The feeding can be done pneumatically for example. Yet, coated parts cannot be detected (Ditze and Scharf 2008). Main obstacles for the investing in such processing plants are the missing economic incentives.

Gesing and Dubreuil (2008) assume that approximately 80,000 t magnesium in old cars could be recycled worldwide. However, a part thereof is separated and used for the desulphurization of steel. A large part is processed to alloys together with aluminium. Gesing and Dubreuil (2008) report that this results in a loss of a part of the magnesium as magnesium chloride as otherwise the composition of the alloy would be wrong. It is doubted that this is common practice in the aluminium industry. Apart from the use in aluminium alloys, steel production and new magnesium products are potential markets for secondary magnesium (Gesing and Dubreuil 2008). There is no data available about the split into the different uses or the share of secondary magnesium coming from the automotive industry. As a result of the higher market volume of aluminium, the absolute amount of secondary material is higher. That leads to an economic relevant amount of recyclable material whereby the recovery rate is higher. It can be assumed, that approximately 90% of aluminium, coming from vehicles, can be recycled. In Europe, the absolute amount of used secondary aluminium, coming from the recycling of old vehicles, was 673,000 t (European Aluminium Association 2008). The secondary material is used in various aluminium products and is not supplied to dissipative application, in contrast to magnesium.

Determining average recovery rates for magnesium is difficult. The yield for the recycling of prompt scrap from manufacturing of automotive components is 85 to 95 % depending on component type and material losses. The rate for scrap from car dismantling is estimated to be 80 to 90 %, dependent on the separation efforts. High uncertainties exist for the yield for the recycling of sorted scrap from shredders. As magnesium usually ends up in the NF or light metal fraction, there is no validated data on average recovery rates for magnesium. The possible yield depends strongly on the separation technology and composition of the shredder material. Tests on this rate showed recovery yields from 50 to 75 % of the original magnesium content. As for aluminium, recycling yields of 90 % are reported for automotive components, this rate is applied for the overall light metal fraction in this study. The influence of the recycling rate is analyzed in part II of this study.

## 5.4 Life Cycle Inventory for Magnesium Recycling

### 5.4.1 Inventory for Recycling Processes

The recycling of magnesium within the aluminium cycle is seen as standard scenario for magnesium end-of-life. Figure 33 shows the process steps of the end-of-life of a magnesium vehicle component. After dismantling and shredding, the light metals are separated from the rest via air separation. The light metal fraction is assumed to contain 30 % magnesium. It is separated via air separation from the shredder fraction. The light metals are then transported to an alloying plant where the material is cleaned and milled. For alloying, the material has to be remelted and alloyed according to the requirements of the specific alloy.

Table 15 shows the energy consumption of vehicle treatment and processing of the aluminium alloy. The overall energy and material consumption of the aluminium alloy making is taken from the ecoinvent database. The reference flow of this model is 1 kg material (aluminium alloy). The yield of the light metal fraction is assumed to be 90 %. The sources for aluminium in alloy production are: 20 % primary Al, 47 % secondary from new scrap, and 33 % secondary from old scrap. For the end-of-life vehicle processing, only the treatment of the magnesium parts is accounted.

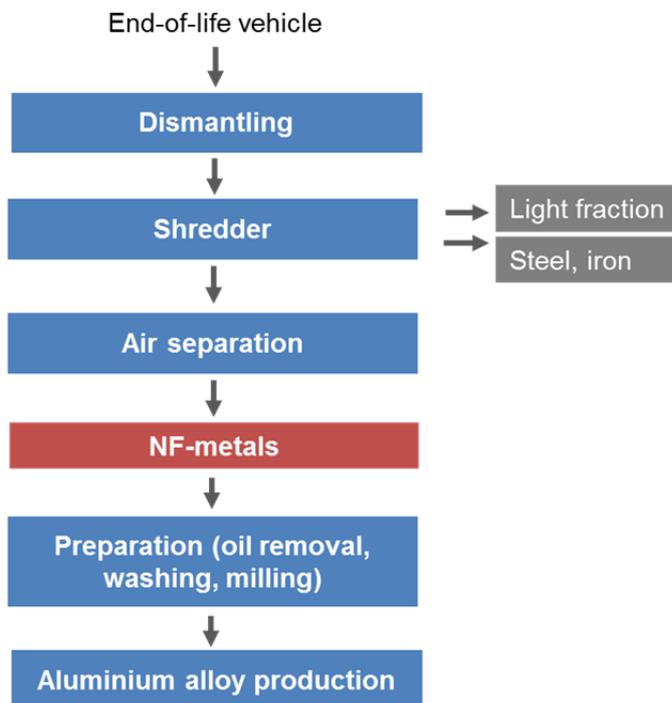
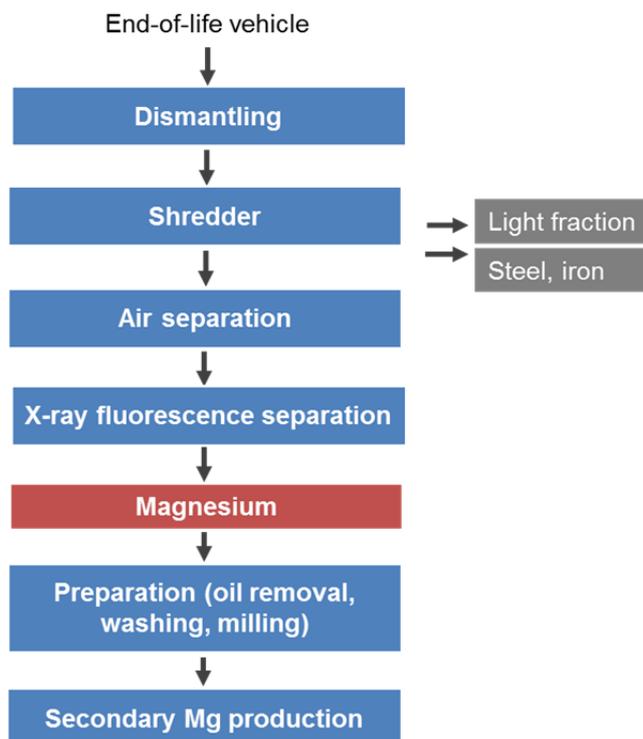


Figure 33: Process steps of standard scenario for magnesium end-of-life (Ehrenberger and Friedrich 2013)

**Table 15: Energy consumption of the processes of the standard scenario**

Recycling Step	Electricity [kWh/kg Mg]	Flow Capacity [kg/h]	Performance [kW]
<b>End-of-life vehicle treatment</b>			
Dismantling			
Shredder	0.025	9500	680
Air Separation	0.043	4700	140
Magnet Separation	0.023	9500	150
NF-Metals	0.127	350	40
Transport	(300 km)		
<b>Preparation</b>			
Oil removal	0.004	2000	7.5
Washing	(water: 0.001 m <sup>3</sup> )		
Milling	0.025		
<b>Aluminum alloy production</b>			
Melting Furnace	0.6		
Holding Furnace	0.083		
Conveyor	0.002		
Ingot Casting Conveyor	0.064		
Others	0.8		

As alternative path, the recovery of pure magnesium is modelled. The processes for the end-of-life vehicle treatment are again dismantling, shredding and air separation. Magnesium and aluminium are then separated by X-ray fluorescence separation (Figure 34). The magnesium is then transported to the recycling plant, where it is cleaned and remelted. This will be a viable recycling path whenever it is economically feasible or when there is too much Mg on the market. Table 16 shows also input data for secondary magnesium production. The reference flow is 1 kg of magnesium.



**Figure 34: Process steps of the alternative scenario for magnesium end-of-life (Ehrenberger and Friedrich 2013)**

**Table 16: Energy consumption of the processes of the alternative scenario**

Recycling Step	Electricity [kWh/kg Mg]	Flow Capacity [kg/h]	Performance [kW]
<b>End-of-life vehicle treatment</b>			
Dismantling			
Shredder	0.025	9500	680
Air Separation	0.043	4700	140
Magnet Separation	0.023	9500	150
NF-Metals	0.127	350	40
X-Ray Fluorescence Separation	0.024	800	13.5
<b>Preparation</b>			
Oil removal	0.004	2000	7.5
Washing	(water: 0.001 m <sup>3</sup> )		
Milling	0.025		
<b>Secondary Mg Production</b>			
Melting Furnace	0.148 (R134a: 0.0005 kg fluxes: 0.1 kg heat: 2.4 MJ)		

### 5.5 Environmental Indicators for Magnesium Recycling

The end-of-life process consists of two parts: the treatment of the end-of-life vehicle, where the components and materials of the vehicle are recovered, and the further processing of the light metal fraction, where magnesium is treated as element for aluminium alloys. In Figure 32, the results for the impact categories are depicted. As the energy consumption for the vehicle treatment is much lower than for the aluminium alloy processing, the impact of this process is significantly lower as well. For the global warming potential, the vehicle treatment contributes with 4 % to the overall emissions of 3.8 kg CO<sub>2eq</sub> / kg material. For other categories, the contribution ranges from 2 to 7 %. The dominant factor for both parts of the end-of-life is the energy consumption. Material consumptions during aluminium alloy processing plays a minor role and does not influence the overall balances.

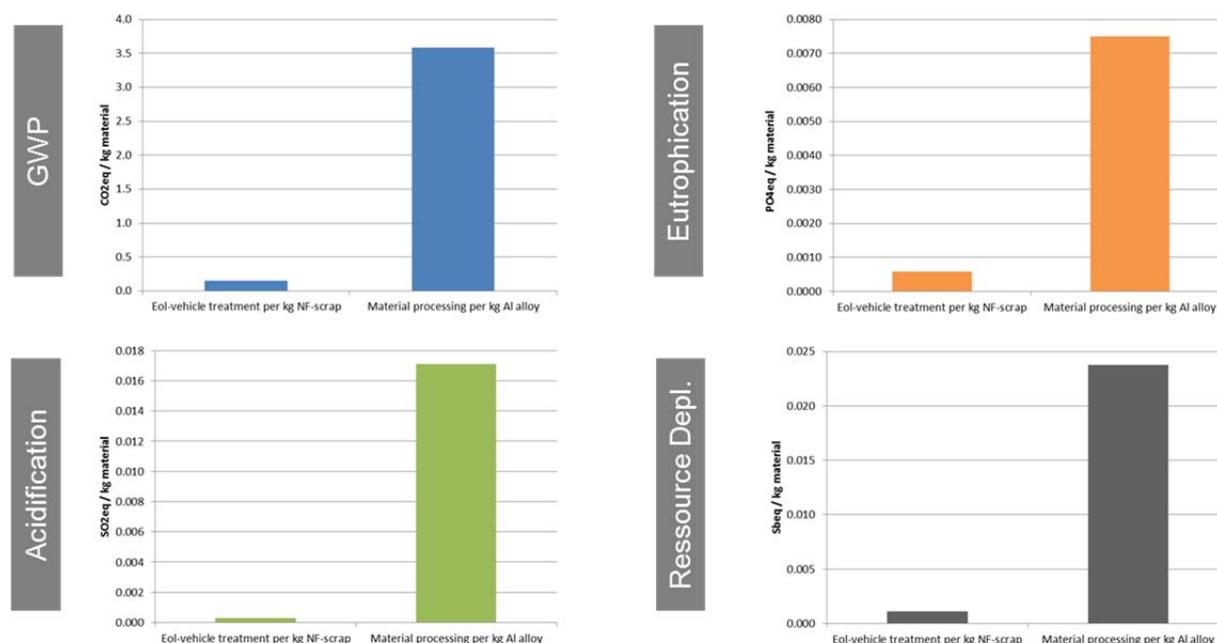


Figure 35: Results of impact assessment for standard scenario (Ehrenberger and Friedrich 2013)

In the alternative scenario, the recovery of magnesium itself is modeled. Figure 36 shows the results for the impact assessment of this scenario. Due to the lower energy consumption of the magnesium recovery process, the overall emissions and resource depletion are lower compared to the standard scenario. The greenhouse gas emissions amount to 1.1 kg CO<sub>2eq</sub> / kg material. As the data source for this scenario is only one plant, the representativeness of this model is not evaluated. The treatment of the end-of-life vehicle is – similar to the standard scenario – of minor importance except for the eutrophication category.

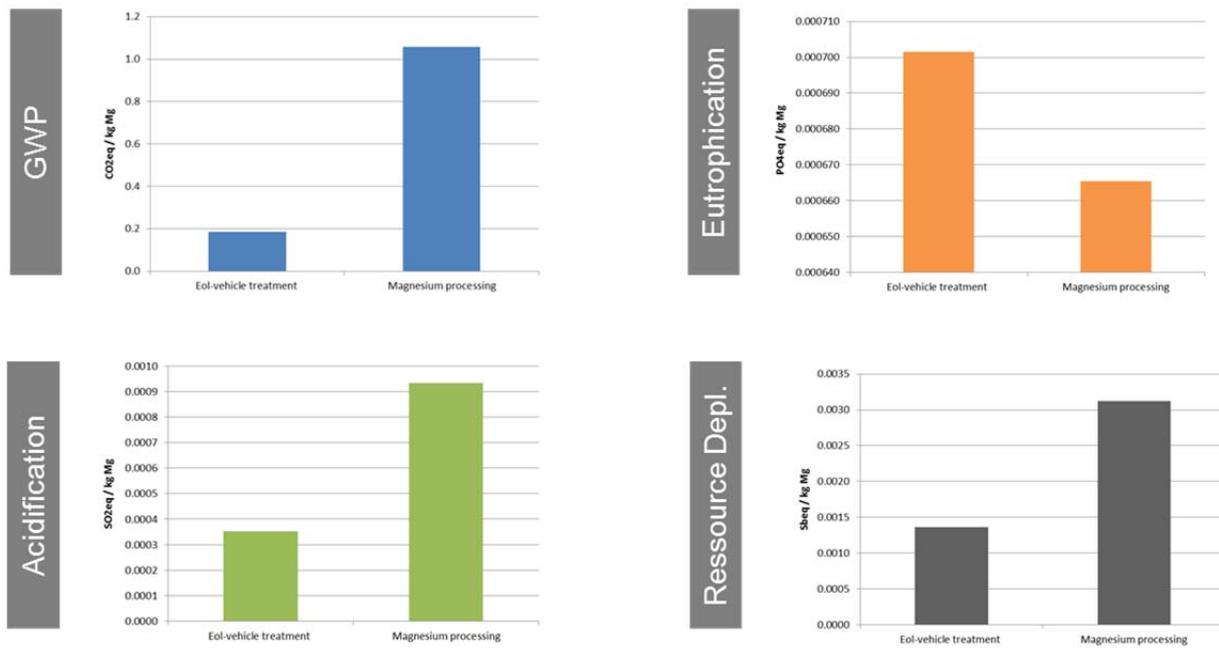


Figure 36: Results for impact assessment of alternative end-of-life scenario (Ehrenberger and Friedrich 2013)

## 6 Conclusions

The evaluation of the current magnesium production has shown that the Pidgeon process has been subject to significant technological improvements in the past years. The most important change is that in 2011 all magnesium producers in China use gas as energy source for the Pidgeon process. Additionally, a waste heat recovery in reduction furnaces is standard. Many producers introduced further measures to improve the process efficiency and reduce fuel consumption. The assessment of the Pidgeon process of 2011 leads to emissions of 25.8 kg CO<sub>2eq</sub> / kgMg in average. When the use of coke oven and semi coke oven gas as waste from other production systems is credited, the weighted average of the Pidgeon process is 19.9 kg CO<sub>2eq</sub> / kg Mg.

The usages of natural gas (23.7 kg CO<sub>2eq</sub> / kg Mg) and coke oven gas (23.6 kg CO<sub>2eq</sub> / kg Mg) show the lowest emissions. Considering the decrease of emissions in the different process steps, the reduction process bears much more reduction potential than calcination. To a certain extent this is because of the CO<sub>2</sub> emissions from chemical reaction during calcination, which amount to 5 - 6 kg per kg Mg and which cannot be avoided. In general, stricter regulation for exhaust gases could further decrease SO<sub>2</sub> and NO<sub>x</sub> (the latter not being limited at all up to now) emissions, as these emissions can be decreased technically.

Further major technical improvements are the use of waste heat from slag and the use of vertical retorts. These measures are not expected to be used broadly in the near future. The production of FeSi contributes considerably to all impact categories. As notable reductions in energy and material consumption cannot be expected this will remain a major impact source for the Pidgeon process. Critical aspects in this analysis are the lack of data for gas compositions and for production of gases.

The global warming potential for the exemplary electrolysis is 17.8 kg CO<sub>2eq</sub> per kg magnesium due to fuel switch in electricity production from oil to natural gas. The energy supply remains as main influencing factor for impact assessment. A further decrease of environmental impact is possible with e.g. more efficient energy production or renewable energy. The use of HCF 134a reduces greenhouse gas emissions additionally. The electrolysis process still causes less emission than the Pidgeon process, though the difference has become smaller.

The manufacturing of the components leads to slight advantages for the magnesium parts in a gate to gate analysis due to the fact that less material has to be processed. Main influencing parameters for the assessment are the type of cover gas used and the amount of production waste. In case of die casting, there are several technical measures that would lead to a lower energy consumption of the process. Regarding the design of parts, a reduction of production scrap would be beneficial from an environmental point of view. Though most of the scrap is reused for casting, the processing of additional material requires energy and higher material consumptions. Furthermore, the direct reuse of production scrap could save energy as one melting step could be saved.

The recycling processes do not contribute significantly to life cycle emissions, but crediting reuse of magnesium has major influence on overall emissions of the life cycle. The lack of statistical data on magnesium fate makes the evaluation of end-of-life magnesium parts difficult. The standard recycling path for magnesium is its further use as aluminium alloy as the aluminium market is expected to be big enough to absorb all end-of-life magnesium. A significant phase out of magnesium during aluminium alloy production and significant rate of hand-sorting as stated in former publications cannot be observed today. But still, economic restrictions and a lack of secondary magnesium alloy applications impede the recycling of magnesium as “pure” metal in the near future.

Generally, the reuse of magnesium shows significantly lower environmental impacts than primary production. Thus, efforts in establishing the reuse of magnesium is a beneficial way of improving the environmental performance of magnesium for transport applications.

**Summing up it can be stated:**

- The magnesium production with Pidgeon process as a rule shows the higher CO<sub>2</sub> emissions than magnesium from electrolysis.
- Due to technical process improvements the emission values have dropped significantly in the last few years. Crediting the use of production waste from the coke and semi coke industry leads to further savings of greenhouse gas emissions.
- The electrolytic process of Mg has basic CO<sub>2</sub> advantages compared to the general Pidgeon process. These advantages are important especially when using renewable energies.
- Attractive alternatives with respect to energy and emissions are for example the silicothermic (Bolzano) process used in Brazil or maybe new projects based on the use of cost attractive and renewable energies (e.g. the planned electrolysis site in Qinghai, China).
- The recycling process does not contribute significantly to the emissions. To credit reuse of Mg shows an important influence to LCA.

## **PART II: Life Cycle Performance of Magnesium in Transport Applications in terms of Global Warming Potential**

# 1 Introduction

Magnesium and aluminium offer considerable potential as lightweight materials in transport applications. Whenever parts of road vehicles, trains, aircraft etc. effect a reduction of the weight that has to be moved, fuel and thus emissions to the environment can be reduced. In automotive construction, the potential of reducing CO<sub>2</sub> emissions has become more and more important in the past years due to legal requirements and consumer demand. Aviation is even more sensitive to weight reduction as this is even more economically important due to the high energy demand and mileages of aircraft.

In general, magnesium shows higher emissions during component production compared with aluminium. These higher emissions should be compensated during use stage. In this report, we analyse the use of both metals for an exemplary road vehicle component and an aircraft application. The amount of fuel and emissions that can be saved depends on the weight savings. For automotive applications, several studies have shown that due to the high weight savings compared to the classical material steel, the use of magnesium and aluminium can be beneficial from an ecological point of view (Hakamada, Furuta et al. 2007; Tharumarajah and Koltun 2007; Ehrenberger, Schmid et al. 2008; Dubreuil, Bushi et al. 2010). Magnesium components can save about 25 % of weight compared to aluminium. Thus, for the calculation of potential ecological break-even points, the source of the primary metals and the end-of-life stage are expected to have more influence on the overall balance than in comparisons to steel.

In the following, we first present the methodological approach of evaluation the whole life cycle of two magnesium products (chapter 2). We then analyze the life cycle of a steering wheel in a road vehicle (chapter 3) and then present the comparison of magnesium and aluminium door parts for aircraft (chapter 4). In both application examples, only greenhouse gas emissions are presented as an environmental indicator. This impact category is major driver in lightweight design for transport, thus we concentrate on the evaluation of this indicator.

## 2 Goal and Scope Definition

### Goal

Part II of this report represents the results of module 3 of the IMA LCA study as well as the analysis of the overall life cycle of the components which are exemplarily analyzed in the study (as shown in Figure 6). In the following chapters, the calculation of the use stage of the components presented in part I of the report is evaluated in terms of greenhouse gas emissions. In case of the steering wheels, the use in a gasoline passenger car for a driven distance of 200,000 km is calculated and represents the functional unit of this model. The calculation of fuel savings is based on the energy consumption in the new European driving cycle (NEDC) for a compact class car. The use of the aircraft parts is analyzed for application in an A320 aircraft. An exemplary use case representing a flight over a distance of 4,100km has been defined to calculate the emissions during aircraft operation. The functional unit of this model is the use of magnesium parts in a certain number of flights. Furthermore, the overall balances of emissions per year and per lifetime of an aircraft are estimated.

The analysis aims to assess the potential advantages of the use of magnesium in passenger cars and aircrafts in comparison with aluminium. By considering the component examples, we analyze the main influencing factors for both applications.

### Data collection and data quality

The input data for the production and end-of-life of both component examples are taken from the energy and material flow models for primary magnesium production, processing of magnesium and aluminium as well as end-of-life of magnesium and aluminium components which are described in part I of this report. The data on primary aluminium are taken from literature.

For the calculation of fuel saving during vehicle and aircraft operation, data on the dependence of fuel consumption on weight reduction is necessary. In case of the use of the steering wheel in a car, the gasoline consumption is calculated according to literature data. The fuel savings for the aircraft application are determined by using the DLR model VAMPzero which is a conceptual design tool for aircraft.

The main input parameters for the calculation of the life cycle greenhouse gas emissions for the magnesium and aluminium components are listed in Table 17. The data are calculated in this report except from the primary production of aluminium (European Aluminium Association 2008; Gao, Nie et al. 2009; da Silva, d'Souza et al. 2010). The average world scenario is based on a combination of GHG emissions from average Pidgeon process and electrolysis. A share of 83 % Pidgeon process and 17 % electrolysis is assumed. The term "Pidgeon process – average with credits" refers to the Pidgeon process scenario for coke oven and semi coke oven gas in which these gases credited as waste gases (see chapter 3). The recovery rates are assumed to be equal for both metals. The magnesium component is treated together with the aluminum fraction in the end-of-life vehicle treatment and processed together with the aluminum as alloying element.

**Table 17: Overview of component specifications and greenhouse gas emissions for magnesium and aluminium steering wheels**

	Magnesium	Aluminium
<b>Component specifications</b>		
<i>steering wheel - passenger car</i>		
weight	0.55 kg	0.74 kg
alloy	AM50	AlMg3
alloy	AZ91E	A356
<b>Primary magnesium</b>		
Pidgeon - average	25.8 kg CO <sub>2</sub> eq/kg Mg	
Pidgeon - COG	23.6 kg CO <sub>2</sub> eq/kg Mg	
Pidgeon - SCOG	26.7 kg CO <sub>2</sub> eq/kg Mg	
Pidgeon - average with credits	19.9 kg CO <sub>2</sub> eq/kg Mg	
electrolysis	17.8 kg CO <sub>2</sub> eq/kg Mg	
electrolysis incl. credits	14 kg CO <sub>2</sub> eq/kg Mg	
average world	24.4 kg CO <sub>2</sub> eq/kg Mg	
<b>Primary aluminium</b>		
average world		12.7 kg CO <sub>2</sub> eq/kg Al
Europe		9.7 kg CO <sub>2</sub> eq/kg Al
USA		11 kg CO <sub>2</sub> eq/kg Al
China		21.6 kg CO <sub>2</sub> eq/kg Al
<b>Component manufacturing</b>		
steering wheel - die casting	0.8 kg CO <sub>2</sub> eq/FU	1 kg CO <sub>2</sub> eq/FU
door parts - sand casting	39.9 kg CO <sub>2</sub> eq/FU	41.7 kg CO <sub>2</sub> eq/FU
<b>End-of-life</b>		
recovery rate vehicle treatment	90 %	90 %
share of recycled metal	90 %	90 %

### System boundaries and background data

The calculations for the use of magnesium calculations include the entire life cycle of the parts from cradle to grave for the steering wheel used in a passenger car. In this case, "grave" refers to the end of the first life at which the used material is available for a second life. The analysis of the aircraft parts focus on production and the break-even point for the comparison of magnesium and aluminium parts during aircraft operation. The overall balance for this consideration is estimated based on statistical data on aircraft use. The end-of-life of aircraft components is not part of the study as it is not considered to be relevant for the greenhouse gas emissions of this use case.

Background data for fuel production are taken from the ecoinvent database 2.2.

### Functional unit and reference flow

In case of the steering wheels, the use 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 in the new European driving cycle (NEDC) for a compact class car. The analysis focuses on the calculation of the differences in GHG emissions during all life stages of the component. The reference flow is one steering wheel frame (in the following referred to as

“steering wheel”) weighting 0.55 kg when made from magnesium and 0.74 kg when made from aluminium.

The functional unit of the aircraft parts is the use of three door parts (one gearbox and two seal closers) 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 30 a.

### **Categories for impact assessment**

Due to the importance of the greenhouse gas emissions for the decision on lightweight materials, this part of the study concentrates on the evaluation of the potential impacts on climate change. Thus, all results presented in the following chapter refer to the emissions of greenhouse gases expressed as CO<sub>2eq</sub> for a time horizon of 100 years.

### 3 Analysis of Use Stage and Life Cycle of a Steering Wheel

#### 3.1 Input Data for Production and End-of-Life of Component

The production of primary magnesium and the manufacturing of the steering wheel via die casting is described and analyzed in detail in part I of this report. Additionally, the production of primary aluminium and the aluminium steering wheel is evaluated in the first part as well. The life cycle steps of the steering wheel made from magnesium and aluminium are shown in Figure 37. Table 17 gives an overview on the component specifications of the steering wheel and other input parameters for the calculation. These specifications and emission factors are input data for the calculation of the comparative use stage of the steering wheels.

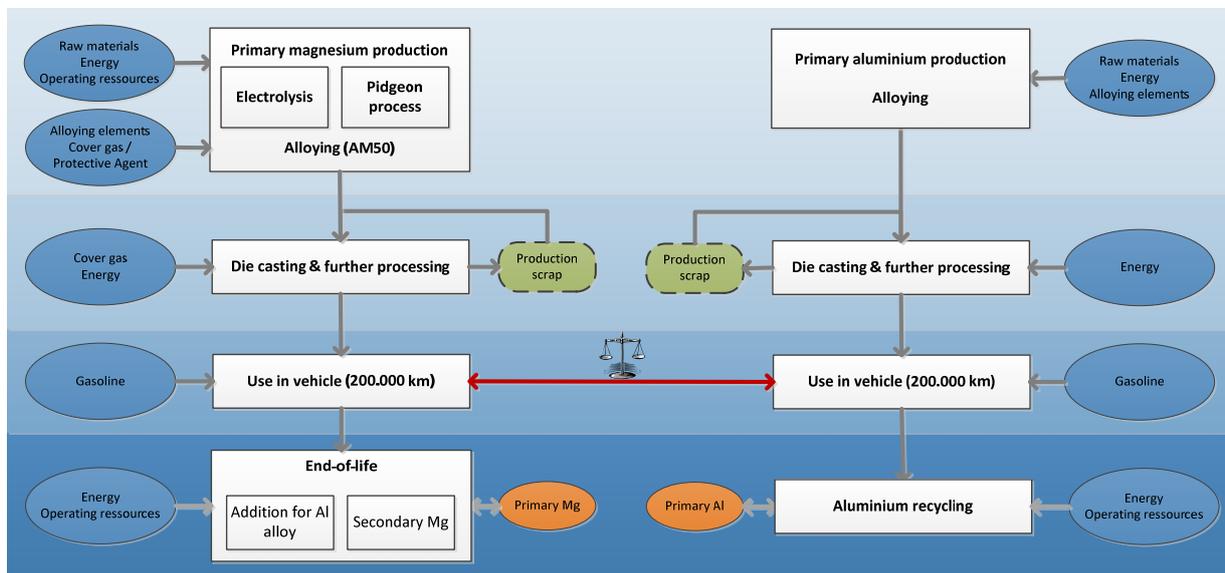


Figure 37: Overview of life cycle of steering wheels

#### 3.2 Calculation of Fuel Savings

One goal of using lightweight materials in vehicles is to save weight and thus fuel during vehicle operation. Fuel savings lead to lower burdens from fuel production and less emission from vehicle operation. The amount of fuel saved is calculated using a fuel reduction coefficient. The absolute value of this coefficient depends on the technical properties of the vehicle, driving cycle, fuel type and other aspects. A range from 0.15 to 0.6 l fuel per 100 km and 100 kg weight saved is reported in literature for passenger cars with internal combustion engine (Espig, Johannaber et al. 2006). Alternative hybrid or electric vehicles provide less potential for energy savings from weight reduction (Redelbach, Klötzke et al. 2012). A fuel reduction value of 0.35 l / 100kg\*100km can be considered as representative for an average European gasoline vehicle. Such a coefficient already includes secondary effects, e.g. the adaption of the drive train (Table 18; Koffler and

Rohde-Brandenburger 2010)). The overall fuel reduction over a life time of a vehicle is characterized by a certain mileage and calculated on component level. Thus, the calculations 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. The fuel saving of a magnesium component compared to an aluminium reference is calculated by (see also (Koffler and Rohde-Brandenburger 2010)):

$$c = (m_{alt} - m_{ref}) \cdot k \cdot 0.01$$

with

c... fuel saving [l / 100km]

m<sub>alt</sub>... mass of alternative component [kg]

m<sub>ref</sub>... mass of reference component [kg]

k... fuel reduction coefficient [l / 100 km\*100 kg]

The fuel reduction coefficient used in this study refers to the standard new European driving cycle (NEDC) for passenger cars.

**Table 18: Fuel reduction coefficients for gasoline and diesel vehicles**

Engine type	No adaptation <sup>a</sup>	Adaptation <sup>a</sup>	Min	Max	Arithmetic mean
Gasoline	0.15	Gear ratio	0.29	0.39	0.32
		Displacement	0.36	0.45	0.39
Diesel	0.12	Gear ratio	0.27	0.30	0.29
		Displacement	0.24	0.29	0.26

<sup>a</sup> Power train adaptation to achieve equal driving performance, e. g., extension of gear ratio or reduction of engine displacement

source: (Koffler and Rohde-Brandenburger 2010)

One key parameter for the analysis of road vehicle components is the fuel reduction coefficient. The coefficient used in this study includes secondary measures, at least when the energy consumption is calculated based on the NEDC. This implies the use of the magnesium component in an optimized car in terms of energy efficiency.

The fuel savings lead to a direct reduction of emission during vehicle operation. CO<sub>2</sub> and other greenhouse gas emissions decrease proportionally to the lower fuel consumption. For other

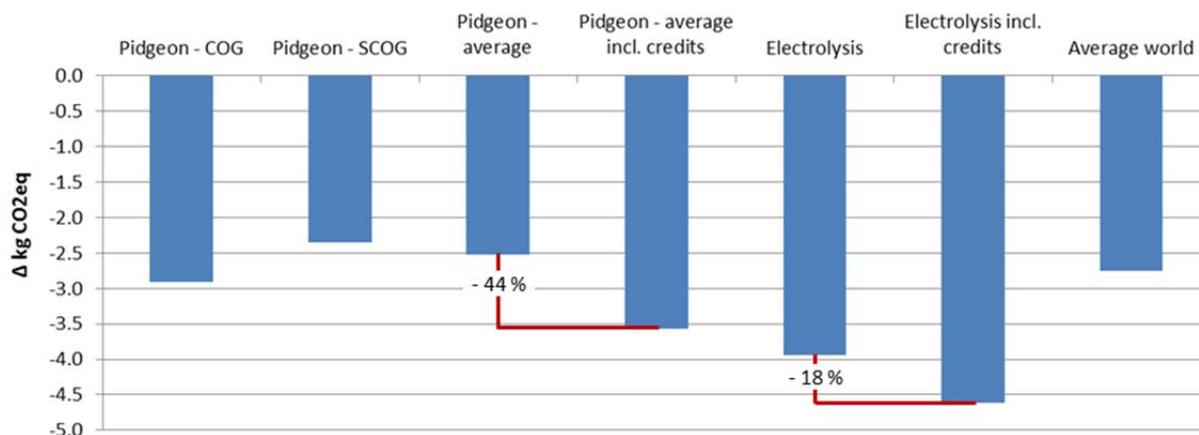
emissions like particles or nitrogen oxides, the development of emissions due to fuel savings is ambiguous. Additionally, less fuel has to be produced which also saves emissions from the upstream process of fuel production. Goal of this analysis is to evaluate, if savings of fuel are high enough to compensate possibly higher resource consumptions and emissions during the production phase of the magnesium component. Then a break-even point within a given mileage can be achieved for greenhouse gas emissions.

The  $\text{CO}_{2\text{eq}}$  factors on gasoline used for the calculations are 522 g  $\text{CO}_{2\text{eq}}$ /l for fuel production and 2380 g  $\text{CO}_{2\text{eq}}$ /l for fuel combustion during vehicle operation.

### **3.3 Results for Impact Assessment**

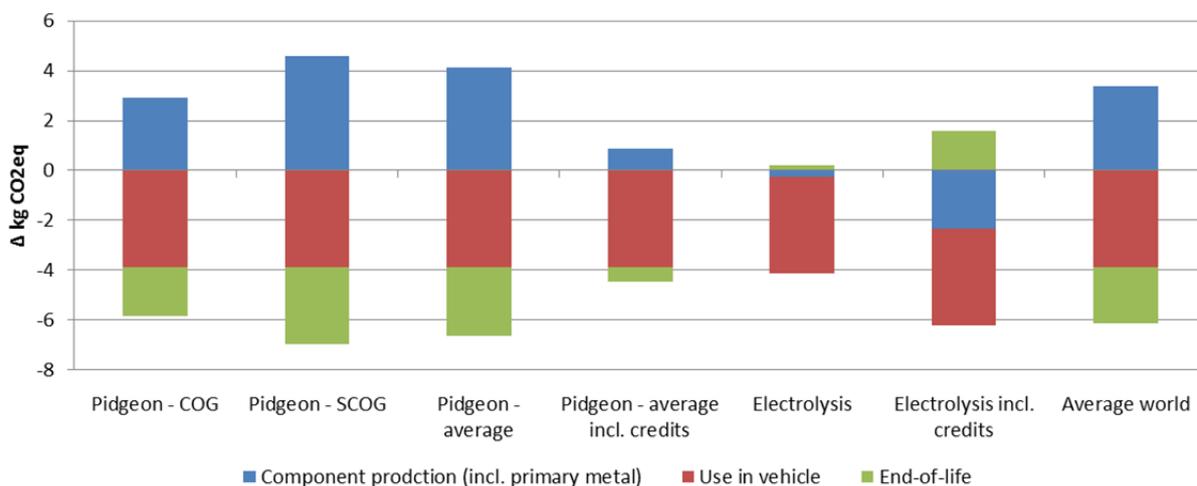
For the ecological assessment of the use of lightweight materials in transport, the use phase has considerable influence on the overall balance. In the following, the results of the use stage calculations in the context of the overall life cycle balance of greenhouse gas emissions is presented for the component example “steering wheel” made from magnesium. The magnesium part is compared to a steering wheel made from aluminum. Only the differences of absolute emissions for component production, use stage and end-of-life are analyzed.

As described in chapter 3.2, the fuel savings are calculated for a middle class passenger car operated with gasoline. The fuel reduction coefficient is 0.35 l / 100kg\*100km. The weight difference of both parts is 0.19 kg (26 %). This weight reduction would not lead to secondary effects in vehicle design, like an adaption of the drive train or other components. The calculation of the use stage implies that the lighter material is used in a weight optimized car. The calculation of the fuel savings using the parameters listed in Table 17 results in  $\text{CO}_{2\text{eq}}$  savings of 3.8 kg from the use stage. Figure 38 shows the overall balances for component production, use stage and end-of-life. The sum of emissions from production and end-of-life of the magnesium steering wheel are subtracted from the emission of the aluminium component. For the use phase, emissions of 3.8 kg  $\text{CO}_{2\text{eq}}$  are accounted as savings for magnesium. The results are calculated according to the source of primary magnesium. For the aluminium reference, a world average is assumed as source of primary metal. The results show a positive net balance of  $\text{CO}_{2\text{eq}}$  emissions for all magnesium production scenarios. The lowest advantage is reached when magnesium from the Pidgeon process based on semi-coke oven gas is used as primary metal. Magnesium from electrolysis leads to the highest savings of  $\text{CO}_{2\text{eq}}$  emissions.



**Figure 38: Overall balance for magnesium steering wheel compared to aluminium steering wheel based on a mileage of 200,000 km**

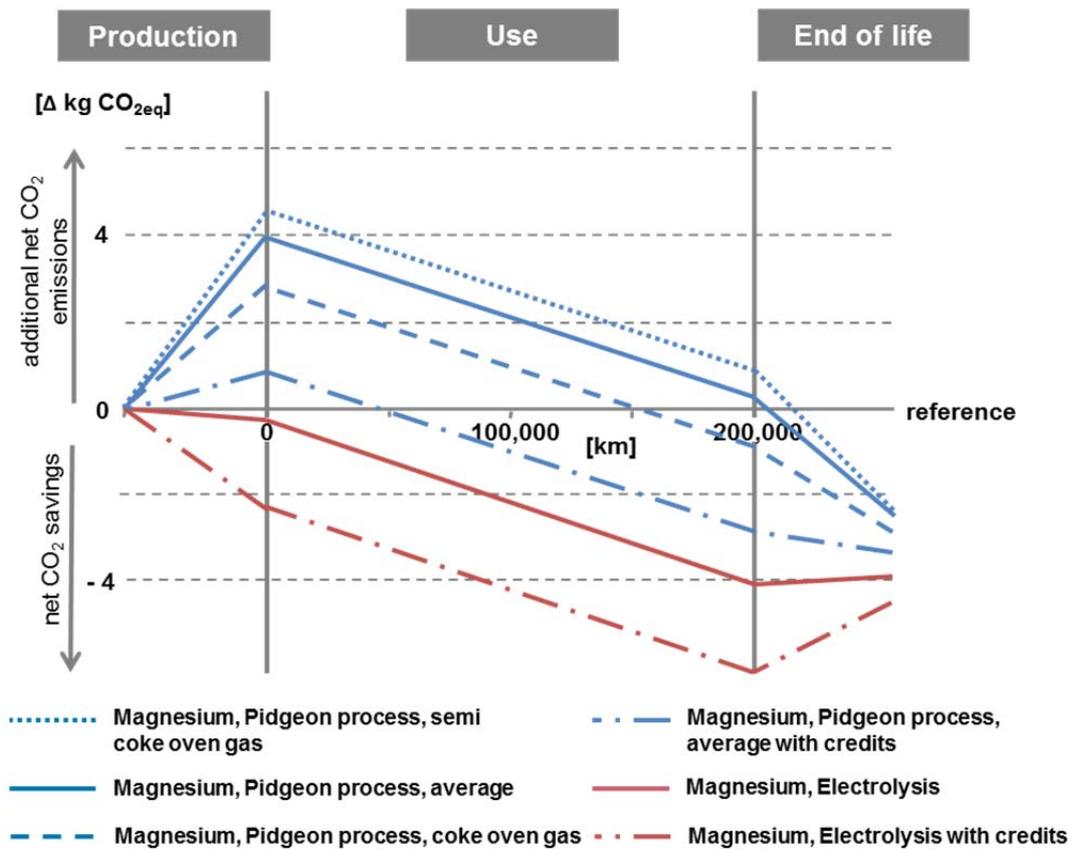
The differences in the single life cycle steps are depicted in Figure 39. Only the differences to the aluminium component are shown. Except for the electrolysis scenarios, the production of magnesium has a positive difference to aluminium which means that the emissions for magnesium are higher in this life stage. The emissions of the steering wheel production based on average Pidgeon process as source of primary magnesium, for instance, amount to 15.4 kg CO<sub>2eq</sub> while the emissions for the aluminium steering wheel are 11.3 kg CO<sub>2eq</sub>. This includes production of primary metals and alloys as well as the manufacturing of the steering wheel via die casting. The emission savings (3.8 kg CO<sub>2eq</sub>) are equal for all magnesium scenarios as they only depend on the weight savings of the steering wheel. The recycling process amounts to emission saving of about 1.7 kg CO<sub>2eq</sub> for the magnesium component. Additionally, a credit for the substitution of primary material is included in the end-of-life calculation. It is assumed that 90 % of the magnesium is recycled and used for aluminium alloy production where primary magnesium can be substituted. For this amount of magnesium, a credit of 100 % is given. This leads to overall savings for the Pidgeon process magnesium scenarios in comparison to aluminium. The credits for the magnesium from electrolysis are lower than for aluminium which in the end leads to a positive difference in the comparative analysis.



**Figure 39: Differences of CO<sub>2eq</sub> emissions for single life cycle steps of magnesium component compared aluminium component**

Figure 40 reveals the break-even points for the main scenarios of magnesium production from Pidgeon process and electrolysis. Again only the differences of the absolute emissions from both material life cycles are depicted. As seen before, the balance of the overall life cycle leads to lower emissions for all magnesium scenarios compared to the aluminium base-line. The break-even point is reached at about 150,000 km for magnesium from a coke oven gas based Pidgeon process. The Pidgeon process based on natural gas would lead to the same break-even point. The Pidgeon process using semi-coke oven gas as fuel does not lead to an amortization of emissions during the mileage of 200,000 km. Due to the high credits given for the substitution of this primary magnesium, net savings can be reached for this scenario after the end-of-life stage. As considerable amounts of magnesium are produced using semi-coke oven gas, the average Pidgeon process also shows a break-even point late in the life cycle of the steering wheel. When the use of coke oven and semi coke oven gas as production waste is credited, a break-even at 46,000 km is reached for the average Pidgeon process.

In case of magnesium from electrolysis, the production of the steering wheel already results in lower emissions compared to the aluminium reference. The credits for the substitution of primary material at the end-of-life are higher for aluminium than for magnesium from electrolysis. This leads to higher CO<sub>2</sub> emissions for this magnesium scenario compared with aluminium in the end-of-life stage. It does not imply that magnesium from electrolysis should not be recycled. This effect rather results from the methodological choices of crediting 100 % of primary metal and of showing only results for CO<sub>2</sub> emissions only. The consideration of further assessment categories like resource depletion would enable a sound evaluation of end-of-life strategies in this case.



**Figure 40: Savings of greenhouse gas emissions during use stage for different magnesium scenarios**

In Table 19, the break-even points for different magnesium and aluminium scenarios are listed. The source of primary aluminium is also relevant for the result. The table shows different sources of primary aluminium. In case of aluminium produced in China, all magnesium scenarios have lower emissions during the production stage. When the aluminium is produced in Europe, the break-even points are generally higher than for the global average figure on primary aluminium. Only the magnesium electrolysis scenario which includes credits for the production of by-products shows lower emission from component production in all cases. The use of renewable energy for magnesium electrolysis would lead to even lower emissions from the production stage. But this also would apply for renewable energy used for aluminium production. As the results for the comparison of GHG emissions are sensitive to both the source of primary metal (and the system boundaries of the primary production system) and the vehicle and fuel consumption parameters of the use stage, General conclusions on the comparison of magnesium and aluminium parts cannot be drawn without ambiguity.

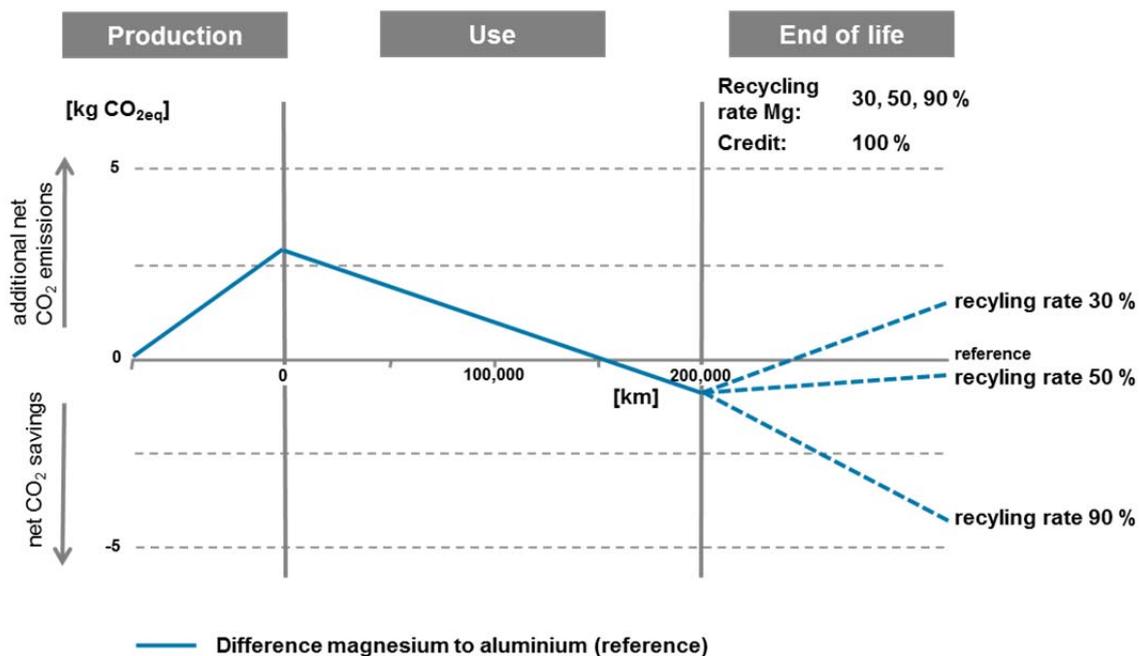
**Table 19: Overview of break-even points according to source of primary metals in km (w/o end-of-life)**

	Al world average 12.7 kg CO <sub>2</sub> eq / kg Al	Al Europe 9.7 kg CO <sub>2</sub> eq / kg Al	Al USA 11 kg CO <sub>2</sub> eq / kg Al	Al China 21.6 kg CO <sub>2</sub> eq / kg Al
<b>Pidgeon - average</b>	212,424	326,802	277,238	< 0
<b>Pidgeon - COG</b>	150,424	264,802	215,238	< 0
<b>Pidgeon - SCOG</b>	237,788	352,166	302,602	< 0
<b>Pidgeon - average with credits</b>	46,151	160,529	110,965	< 0
<b>Electrolysis</b>	< 0	101,347	51,783	< 0
<b>Electrolyse incl. credits</b>	< 0	< 0	< 0	< 0
<b>Average world</b>	174,097	288,475	238,911	< 0

### 3.4 Influence of End-of-Life on the overall Life Cycle Balance

Though, the processing of end-of-life vehicles and material recovery are of minor significance to the overall greenhouse gas balance in comparison to production and use stage in terms of absolute numbers, the assumption of the life cycle steps influence the comparative balance notably. This has been shown for the magnesium use case in (Ehrenberger and Friedrich 2013).

Figure 41 and Figure 42 show the break even curve of the magnesium steering wheel for magnesium from a coke-oven gas Pidgeon process. After the use stage, the component comes to its end-of-life and the metals are recovered. The recycling rate for the aluminium component is 90 % for the material recovery from the end-of-life vehicle and another 90 % for the material which is recycled as secondary alloy. The calculation of greenhouse gas emissions includes the end-of-life vehicle processing, the recycling of the materials to secondary metals and the credit for substituted primary material. The emissions for the recycling process itself are assumed to be equal for both metals per kg metal and only depend on the amount of material. For the magnesium example, the recycling rate is varied. Figure 42 shows the influence of different recycling rates on the overall comparison between the magnesium and aluminium alternatives. The credit for the substitution of primary material in this figure is 100 % for both metals. The influence of the share of recycled material is considerable. If only 30 % of the magnesium is assumed to be recycled, the aluminium with its high recycling rates gets much more credits for saved emissions. The net savings would be absorbed by the low material recovery and the necessity to produce new primary magnesium. A recycling rate of 50 % would lead to a slight advantage for magnesium in the overall balance. In contrast to this, a recycling rate which is similar to the aluminium rate would enhance the net benefit for magnesium notably.



**Figure 41: Influence of recycling rate on the balance of a magnesium component compared to aluminium (Ehrenberger and Friedrich 2013)**

Apart from the recycling rate, the credit given for primary metal substitution plays a major role. Figure 42 shows the influence of the credits on the overall balance. The credit given for the substitution of primary metal and the respective saved greenhouse gas emissions are varied from 0 to 100 %. The influence of this parameter is lower than in case of the recycling rate which is set at 75 % in this example. This is due to the fact that the decision on the crediting procedure is a basic methodological aspect and affects the models for both metals whereas in the figure above the recycling rate is evaluated for magnesium. Thus, this methodological aspect of how to treat the substitution of primary metal has a notable effect on the overall balance. But a higher influence can be noted for the technical aspect of how much magnesium is recycled after the use of the magnesium component.

The influence of such assumptions and parameters for the assessment of magnesium components has to be considered when results of comparative studies are communicated. There is no objective correct way of treating the recycling and reuse of materials, as different opinions exist on the assignment of environmental impacts and credits for primary and secondary products.

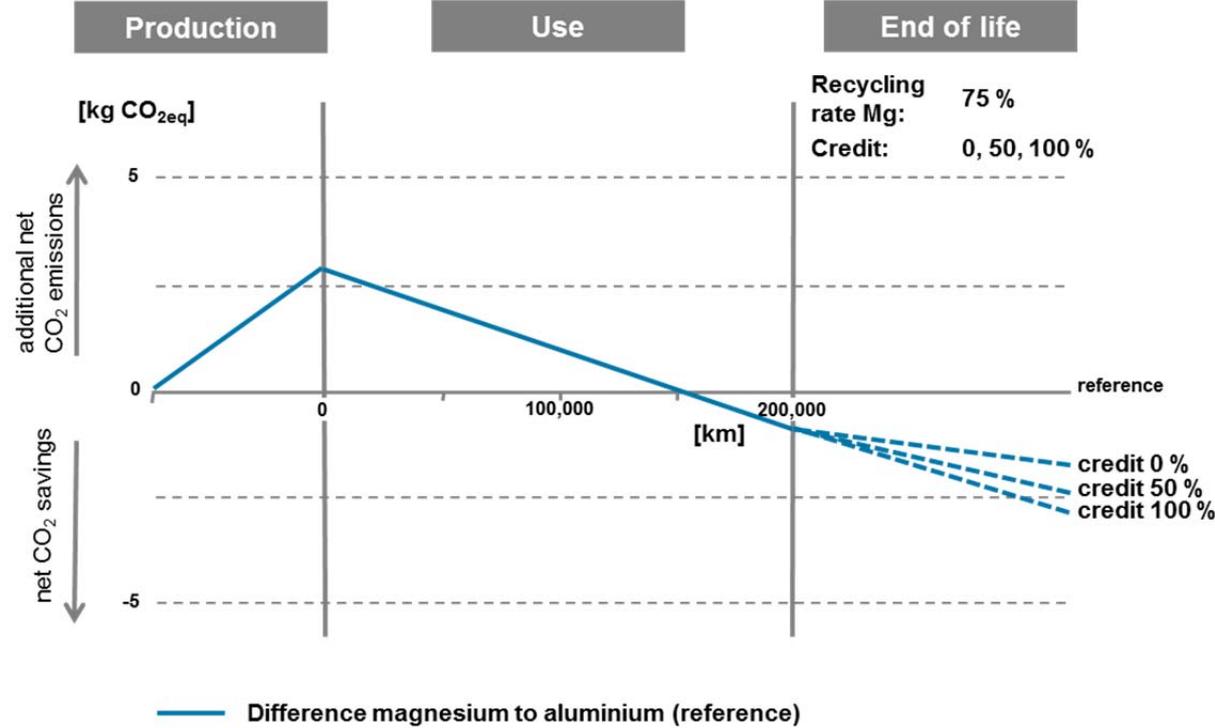


Figure 42: Influence of credits on the balance of a magnesium component compared to aluminium (Ehrenberger and Friedrich 2013)

## 4 Analysis of Use Stage and Life Cycle of Components for Aircraft

### 4.1 Production of Component

The description and assessment of the production of primary metal and the manufacturing of the magnesium and aluminium door parts via sand casting can be found in part I of this report.

Figure 43 shows the life cycle steps of the aircraft parts.

Table 17 gives an overview on the component specifications of the parts and the greenhouse gas emissions from the production and manufacturing processes. These specifications and emission factors are input data for the calculation of the comparative use stage of the aircraft parts.

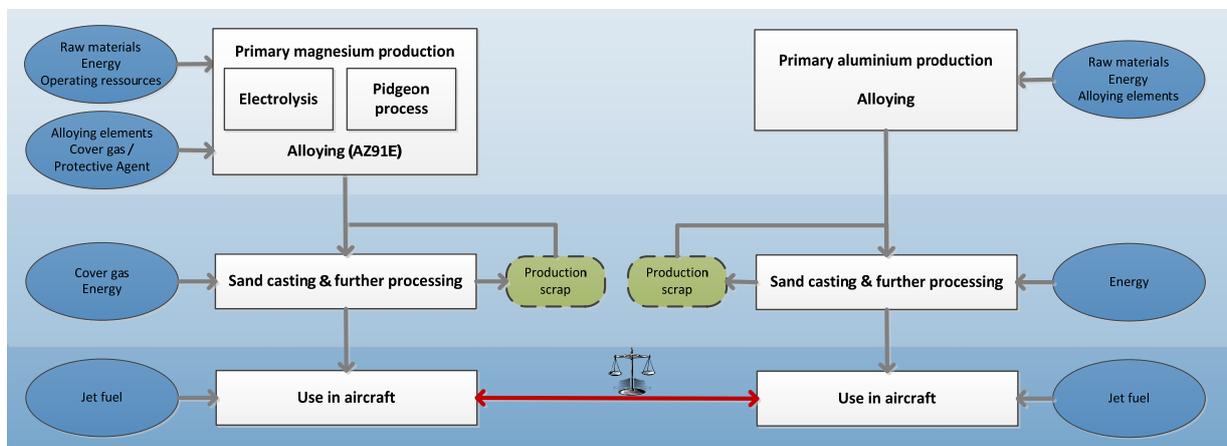


Figure 43: Overview of life cycle of aircraft parts

### 4.2 Calculation of Fuel Savings

The relation of aircraft weight and fuel consumption is calculated using the DLR model VAMPzero. This model analyzes the consequences of changes in aircraft design on different aspects of aircraft operation. For the component example in this report, the fuel consumption is calculated for an A320 which represents a typical aircraft for short and medium haul flights. The correlation of fuel consumption and aircraft weight is analyzed for a flight of 4,100 km and an operating empty aircraft mass (OEM) 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. Thus, the average fuel consumption per km varies in dependence of the flight distance. Unlike for passenger vehicles, there is no standard "driving cycle" which is used for the calculation of fuel consumption.

Table 20 shows the fuel consumption as a function of aircraft weight. The aircraft weight is reduced gradually which leads to a reduction of fuel consumption during aircraft operation. The

fuel savings are calculated for an aircraft of which only the weight is reduced (“frozen geometry” in Table 20). A second calculation has been made for an aircraft with weight reduction and secondary effects due to design adaptations like rescaled wings. We assume that the results of the model are also valid for small weight variations of an aircraft, as the weight savings for the door parts is only 5.8 kg for the entire aircraft. For further calculations of emissions savings, we only consider effect of weight reduction without secondary effects.

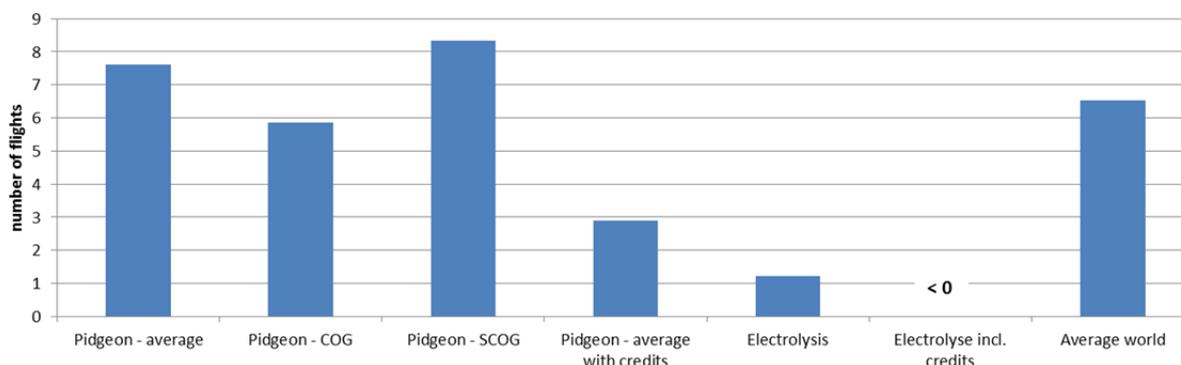
**Table 20: Weight reduction and fuel savings from the VAMPzero model**

Trade Results Reduction Factor	oEM = 41.000kg * factor A320 geometry frozen			oEM = (mWing+ mEngine+...)*factor rescaled wing and steering gear		
	OEM	BlockFuel [kg]	Reduction	OEM	BlockFuel [kg]	Reduction
0%	41000	16956.82		40514.94	16849.91	
1%	40590	16860.60	0.57%	39897.30	16717.38	0.79%
3%	39770	16670.00	1.69%	38683.35	16457.13	2.33%
5%	38950	16481.87	2.80%	37496.92	16203.12	3.84%
10%	36900	16022.31	5.51%	34643.72	15593.50	7.46%

The CO<sub>2eq</sub> emissions from fuel production and aircraft operation are taken from the ecoinvent 2.2 database. For the production of jet fuel, the emissions are 502.3 g CO<sub>2eq</sub>/l and for fuel combustion 3166 g CO<sub>2eq</sub>/l.

### 4.3 Results for GWP

In case of the comparison between aircraft parts of magnesium and aluminium, only few flights are necessary to reach a break-even point for the amortization of higher emissions during component production (Figure 44). When magnesium is produced by electrolysis and the by-products are credited, the production of components has already fewer emissions compared to the aluminium reference. For other magnesium scenarios, the break-even point is reached at latest during the ninth flight. In Table 21, the number of flights in which the break-even points are reached is listed according to different magnesium and aluminium scenarios. Due to high potentials of fuel savings during aircraft operation, the influence of component production and source of primary metal is insignificant.



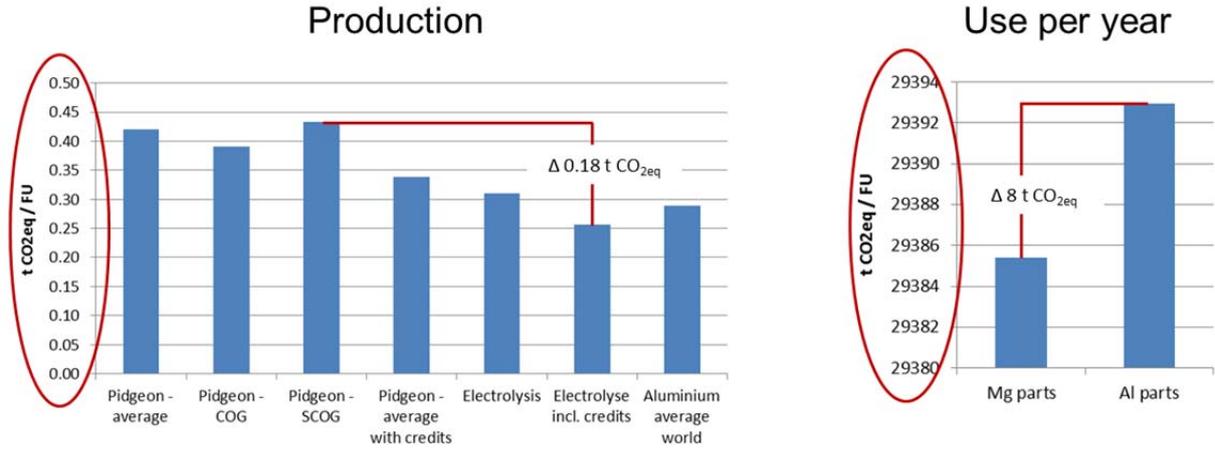
**Figure 44: Number of flights for emission amortization for difference magnesium scenarios**

**Table 21: Overview of break-even points in number of flights according to source of primary metal (w/o secondary measures for aircraft design and w/o end-of-life)**

	Al world average 12.7 kg CO <sub>2eq</sub> / kg Al	Al Europe 9.7 kg CO <sub>2eq</sub> / kg Al	Al USA 11 kg CO <sub>2eq</sub> / kg Al	Al China 21.6 kg CO <sub>2eq</sub> / kg Al
<b>Pidgeon - average</b>	8	11	9	< 0
<b>Pidgeon - COG</b>	6	9	8	< 0
<b>Pidgeon - SCOG</b>	8	12	10	< 0
<b>Pidgeon - average with credits</b>	3	6	5	< 0
<b>Electrolysis</b>	1	4	3	< 0
<b>Electrolyse incl. credits</b>	< 0	1	< 0	< 0
<b>Average world</b>	7	10	8	< 0

The dominance of the use stage in this example is shown in Figure 45. The left figure depicts the absolute CO<sub>2eq</sub> emissions from the production of the components for four aircraft doors. The right figure shows the absolute emissions of the aircraft for an annual operation of about 2 Mio km.<sup>10</sup> The maximum difference to the aluminum reference for component production is 0.18 t CO<sub>2eq</sub>. In contrast to that, the emission savings during aircraft operation amount to approximately 8 t CO<sub>2eq</sub> per year. Assuming a life time of 30 years for an aircraft, the reduction potential for magnesium components is about 226 t CO<sub>2eq</sub>. The following end-of-life of the aircraft does not notably influence the overall emission savings for the magnesium components. The difference to aluminium is 56 kg CO<sub>2eq</sub> at maximum which is less than the difference during component production.

<sup>10</sup> The annual mileage is estimated according to the average annual mileage of the A320 type of three representative airlines: Lufthansa, Air France and United Airlines. The estimation is based on number of aircrafts, flight frequency and average distance per year.



**Figure 45: GHG emissions from production of aircraft parts compared to annual GHG emissions during vehicle operation**

## 5 Conclusions

In general, 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 are amortized considerably. For magnesium produced via electrolysis, the emissions of the production stage are already lower due to the lower amount of material which has to be produced and processed for the magnesium steering wheel. The break-even points for magnesium scenarios based on thermal reduction are reached in a later stage of the use phase. For magnesium from a Pidgeon process based on coke oven gas, the break-even point is reached at 150,000 km. When the use of waste gases is credited for the Pidgeon process, the break-even point of the average Pidgeon process is at 46,000 km. For some scenarios, the amortization takes place in the end-of-life stage under the premise of giving credits for the substitution of primary metal. The results show that magnesium offers a potential for the reduction of greenhouse gas emissions also compared to aluminium. But the production and processing conditions determine to which extend this potential is used.

Considering the fact, that magnesium for electrolysis also could be produced using renewable energy as has been done formerly in Norway, magnesium from such production sites could result in even higher emission savings. The planned magnesium production site in Qinghai, China is a promising way to reduce the impacts from primary magnesium production. The electrolysis plant is planned to use 75 % water power for its electricity supply. First estimations on the greenhouse gas emissions resulted in figures comparable to aluminium electrolysis. As for magnesium parts about 25 % less material has to be processed, this would lead to lower environmental impacts from component production.

In case of using magnesium for passenger cars, the results are sensitive to the fuel reduction coefficient, the background data for aluminium production and the assumptions for end-of-life as well. Additionally, the processing of magnesium is relevant when SF<sub>6</sub> is used as cover gas. Though in today's magnesium processing plants other cover gases like SO<sub>2</sub> or R134a are typically used, the specific production conditions for a magnesium part have to be taken into consideration. For assuring the benefits of magnesium in terms of greenhouse gas emissions, certificates could be given to companies according to the efficiency of primary magnesium production or to avoidance of certain cover gases. This could also be used for magnesium casting companies.

The high energy consumption for aircraft operation and the high fuel reduction potential for aircrafts lead to a fast amortization of emissions from the production stage. Weight savings for application in transportation are related to high reductions of greenhouse gas emissions. The source of primary magnesium influences the break-even point slightly, but does not change the fact of early amortization. To avoid the waste of resources, as much material as possible should be recovered from aircrafts. But the end-of-life stage of aircraft parts has no influence on the overall CO<sub>2eq</sub> balance. The findings of magnesium use in aviation also apply for other means of transportation with high mileage and high energy consumption like high speed trains, for instance.

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The main findings of this comparison are:

- The calculations on the break even points for the passenger car components are sensitive to the source of primary metal. The dependencies of the results on vehicle specific parameters are higher than the differences between the steering wheel alternatives.
- Already with existing magnesium-productions it is possible for the automotive world to gain advantages over aluminium if the magnesium-components are designed specifically to the magnesium-characteristics.
- The break-even points for vehicle part can be reached in a relatively late stage of vehicle life in case of magnesium produced by Pidgeon process under the conditions presented in this study. When magnesium is produced by electrolysis, the emissions are already lower in the production stage or in an early stage of the use phase. Newly planned magnesium production facilities are based on the use of renewable energy which will have a positive impact on the environmental performance.
- 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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## Annex

### I) Impact assessment of primary magnesium production

The following tables list the impact assessment results for the production of primary magnesium.

**Table 22: Results of impact assessment for the Pidgeon process**

Greenhouse Gas Emissions [kg CO2eq /kg Mg]									
	Dolomite	Mining	Ferrosilicon	Fluorite	Calcination	Briquetting	Reduction	Refining	Total
Producer Gas	0.3		8.7	0.1	8.5	0.6	6.6	0.8	25.48
Coke Oven Gas	0.3		8.7	0.1	8.0	0.6	4.6	0.8	23.10
Semi Coke Oven Gas	0.3		8.7	0.1	9.0	0.6	6.7	0.8	26.16
Natural Gas	0.3		8.7	0.1	8.6	0.6	4.3	0.7	23.22
Acidification [kg SO2eq /kg Mg]									
	Dolomite	Mining	Ferrosilicon	Fluorite	Calcination	Briquetting	Reduction	Refining	Total
Producer Gas	0.002		0.08	0.001	0.00	0.01	0.03	0.00	0.12
Coke Oven Gas	0.002		0.08	0.001	0.01	0.01	0.03	0.00	0.13
Semi Coke Oven Gas	0.002		0.08	0.001	0.01	0.01	0.03	0.00	0.14
Natural Gas	0.002		0.08	0.001	0.01	0.01	0.08	0.01	0.18
Eutrophication [kg PO4eq /kg Mg]									
	Dolomite	Mining	Ferrosilicon	Fluorite	Calcination	Briquetting	Reduction	Refining	Total
Producer Gas	0.0002		0.0067	0.0002	0.0004	0.0005	0.0039	0.0001	0.0120
Coke Oven Gas	0.0002		0.0067	0.0002	0.0005	0.0005	0.0040	0.0002	0.0122
Semi Coke Oven Gas	0.0002		0.0067	0.0002	0.0006	0.0005	0.0042	0.0002	0.0124
Natural Gas	0.0002		0.0067	0.0002	0.0004	0.0005	0.0038	0.0001	0.0119
Resource Depletion [kg Sbeq /kg Mg]									
	Dolomite	Mining	Ferrosilicon	Fluorite	Calcination	Briquetting	Reduction	Refining	Total
Producer Gas	0.00		0.07	0.00	0.02	0.00	0.04	0.00	0.1413
Coke Oven Gas	0.00		0.07	0.00	0.03	0.00	0.04	0.01	0.1521
Semi Coke Oven Gas	0.00		0.07	0.00	0.04	0.00	0.06	0.01	0.1732
Natural Gas	0.00		0.07	0.00	0.03	0.00	0.03	0.01	0.1405

**Table 23: Results of impact assessment for magnesium electrolysis and credits for by-products**

	Raw Material Preparation	Electrolysis	Casting	Others	Electrolysis - Total	Credit Cl2	Credit KCl	Net Total
Greenhouse Gas Emissions	3.4	10.7	1.9	2.3	18.2	-2.64	-1.14	14.4 kg CO2eq /kg Mg
Acidification	0.0028	0.0120	0.0009	0.0028	0.0185	-0.01	0.00	0.0017 kg SO2eq /kg Mg
Eutrophication	0.0005	0.0017	0.0001	0.0004	0.0027	-0.01	0.00	-0.0079 kg PO4eq /kg Mg
Resource Depletion	0.0252	0.0913	0.0065	0.0197	0.1427	-0.02	-0.01	0.1144 kg Sbeq /kg Mg

### II) Cover gas consumption and emissions for die casting process

The basic data for the calculation of the consumption of cover gases is given in Table 24. The averaged emission rates are:

- SF<sub>2</sub> – air- mixture: 1.07 kg SF<sub>6</sub> / t metal
- R134a – CO<sub>2</sub> – mixture: 6.41 kg CO<sub>2</sub> / t metal and 0.01 kg R134a / t metal

Regarding the use of SO<sub>2</sub>, only data for the ratio SO<sub>2</sub> / dry air is given. The mass ratio of SF<sub>6</sub> is reported with 0.2 % and the mass ratio of SO<sub>2</sub> with 0.5 – 2 % in dry air. We assume that the volume of the covering gas layer is equal and calculate the SO<sub>2</sub> consumption according to the density of SF<sub>6</sub> and SO<sub>2</sub> (with 1 % SO<sub>2</sub> in dry air).

- density SO<sub>2</sub> = 2,73 kg / m<sup>3</sup>

- density SF<sub>6</sub> = 6,63 kg/m<sup>3</sup>
- factor for mass ratio = 1,0% / 0,2% = 5
- required quantity SO<sub>2</sub> = required quantity SF<sub>6</sub> / density SF<sub>6</sub> \* density SO<sub>2</sub> \* factor
- required quantity SO<sub>2</sub> = 1,07 kg/t / 6,63 kg/m<sup>3</sup> \* 2,73 kg/m<sup>3</sup> \* 5
- required quantity SO<sub>2</sub> = 2,2 kg/t

**Table 24: Base data for emissions and consumption of cover gases in die casting process (data source: (EPA 2004))**

Original Table 5-6 from EPA (2004)

Die Casting Machine	Cover Gas Mixture	GWP Weighted Gas Flow Rate [g/hr]						
		CO2	HFC-134a	SF6	CH4	N2O	C2F6	C3F8
Cold#32	HFC-134a/CO2	1094	1392			10	143	0
Cold#32	HFC-134a/CO2	1026	850			9	94	
Cold#32	HFC-134a/CO2	1090	1107			10	84	
Cold#32	SF6/Air	6		3956311		9		
Cold#32	SF6/Air	2		4021426		3		
Cold#32	SF6/Air	1		3907798		4		
GWP [kg CO2-Eq./kg]		1	1300	22200	5700	296	11900	8600

Die Casting Machine	Cover Gas Mixture	Gas Flow Rate [g/hr] = GWP Weighted Gas Flow Rate / GWP						
		CO2	HFC-134a	SF6	CH4	N2O	C2F6	C3F8
Cold#32	HFC-134a/CO2	1094.00	1.07	0.00	0.00	0.03	0.01	0.00
Cold#32	HFC-134a/CO2	1026.00	0.65	0.00	0.00	0.03	0.01	0.00
Cold#32	HFC-134a/CO2	1090.00	0.85	0.00	0.00	0.03	0.01	0.00
Cold#32	SF6/Air	6.00	0.00	178.21	0.00	0.03	0.00	0.00
Cold#32	SF6/Air	2.00	0.00	181.15	0.00	0.01	0.00	0.00
Cold#32	SF6/Air	1.00	0.00	176.03	0.00	0.01	0.00	0.00

Die Casting Machine	Cover Gas Mixture	Metal Troughput (Table 1-2)		Emissions [g/kg]		
		[lbs/hr]	[kg/hr]	CO2	R134a	SF6
Cold#32	HFC-134a/CO2	368	166.92	6.554	0.006	0.000
Cold#32	HFC-134a/CO2	368	166.92	6.147	0.004	0.000
Cold#32	HFC-134a/CO2	368	166.92	6.530	0.005	0.000
Cold#32	SF6/Air	368	166.92	0.036	0.000	1.068
Cold#32	SF6/Air	368	166.92	0.012	0.000	1.085
Cold#32	SF6/Air	368	166.92	0.006	0.000	1.055

### III) Survey among die cast experts

The results of the survey on the use of cover gases and the performance of die casting is shown in Figure 46.

**1. Use of cover gas**

1 = most important ,..., 4 = least important

	rank							share					
SF6	2	3	4	2	1	3	2	30%	10%	30%	70%	20%	20%
SO2	1	2	2	1	1	2	1	35%	30%	50%	30%	30%	80%
R134a (C2H2F4)	3	1	3	3	3	1	1	25%	20%	10%	10%	40%	10%
3M Novec 612 (C6F12O)	4	4	1	3	4	4	4	10%	40%	10%	10%	10%	10%

**2. Product quality**

Typical output "raw component" (before further processing) for 100% alloy

Kreuzen Sie an, wie Ihrer Erfahrung nach das Verhältnis „guter Guss“ zu eingesetzter Legierung ist (Angaben in %).

Als Beispielbauteil für Ihre Einschätzung soll ein Magnesiumlenkrad dienen.

50%	<input checked="" type="checkbox"/>												
60%			<input checked="" type="checkbox"/>										
70%				<input checked="" type="checkbox"/>									
80%		<input checked="" type="checkbox"/>											
90%					<input checked="" type="checkbox"/>								<input checked="" type="checkbox"/>

Typical output "end product" for 100% alloy

Kreuzen Sie an, wie Ihrer Erfahrung nach das Verhältnis „guter Guss“ zu gesamter Ausbringungsmenge ist (Angaben in %).

Als Beispielbauteil für Ihre Einschätzung soll ein Magnesiumlenkrad dienen.

70%				<input checked="" type="checkbox"/>									
80%					<input checked="" type="checkbox"/>			<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>			<input checked="" type="checkbox"/>
90%		<input checked="" type="checkbox"/>											
others:	85%												

Amount of production waste in aluminium die cast is usually lower than in magnesium die cast

yes													
no	<input checked="" type="checkbox"/>												

**3. Type of furnace used**

electric operated	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
operated with natural gas								<input checked="" type="checkbox"/>

**Figure 46: Overview on answers of die casting questionnaire**

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## Critical review of „Life Cycle Assessment of Magnesium Components in Vehicle Construction“

Author of the LCA study: Simone Ehrenberger, Deutsches Zentrum für Luft- und Raumfahrt e.V.

Reviewer: Dr. Hans-Joerg Althaus

Review done between: 13.4.2013 and 28.04.2013

This report consists of two main parts which document the procedure taken for the review (part 1) and the review comments to the final report (part 2). In the Annex to this report are two more parts documenting some general comments to the first draft report (part 3), the feedback to the model implementation in Umberto (part 4). The Annex can be obtained from Dr. H.-J. Althaus or the authors of the study.

### Part 1: Review Procedure

The aim of the review is to assess conformity of the LCA study with the relevant ISO standards (ISO 14'040 / 14'044) and with the state of the art in LCA methodology. The review cannot assess the correctness of LCI data since they are based on measurements at industrial producers to which the reviewer has no access. However, the review shall assess their plausibility.

The review is basically done "ex post", i.e. after the first draft of the complete study report was produced. The final version of the report includes some changes made to address the review comments to the first draft.

A thorough review of the first draft report was done and more than 150 comments were fed back to the author of the study. The implementation of most steps of the LCI models in the Umberto Software was shown by the author to the reviewer in a 3 hour web-meeting on April 16<sup>th</sup> 2013. Comments and recommendations made during this session are given in part 4 together with a documentation of the checks performed.

## Part 2: Review of final report

Reviewed item: Draft report with file name "2013-04-26\_IMA\_LCA-Study\_Report\_Part-I-and-II\_Review.docx", received 26.4.2013 by e-mail

### General comments:

The study analyses different product systems. It is based on industry data, mainly from China, for primary Magnesium production processes and on industry data for vehicle component production and end-of-life. The use phase of the components in a car and in an airplane is modelled based on consumption models either reported in literature or specifically calculated. Background data has been retrieved from different databases.

Data and modelling are transparently documented in the report. Data and assumptions seem plausible and the modelling applied fits the purpose.

Goal and Scope definitions are elaborated as ISO 14'040 ff requires. The report is split in two parts. Part 1 deals with production of primary Mg and Mg-alloys and the production and end-of-Life (EoL) of vehicle components from Mg. Part 2 deals with the use phase of the Mg components and compares them to functionally equivalent components made of aluminium. Since the study aims at drawing conclusions on different levels (e.g. compare Mg produced with different technologies, compare use of Mg in different vehicles,...), a division in different parts is sensible if not necessary. It helps to overcome the challenges of the different goals and the many functional units and reference flows which are involved in such a study. Goal and scope definition is done for four systems: 1) primary Mg and Mg alloy production (cradle-to-gate), 2) production of Mg-components (gate-to-gate) and 3) EoL of Mg components used in vehicles (gate-to-gate). Those 3 systems are combined with a use phase model in a cradle to grave (or cradle to cradle) system (4) in which Mg-components in specific vehicles are compared to functionally equivalent aluminium components.

The study follows two different principles to deal with multi-functionality. On one hand, energetic allocation is applied for the co-produced fuel gases for the thermal Mg production process. On the other hand, substitution and credits for Co-products from the electrolysis of Mg are used. Credits are also applied for the EoL modelling. It could be argued if not the same principle would be justified as the default choice for all systems. However, scenarios using the other principle are calculated and sensitivities are transparently shown and discussed. Therefore, the procedure is in full accordance to the respective ISO requirements.

Data quality for the main processes involved in magnesium, magnesium alloy and magnesium component production can be considered very high even though only air emissions for several processes are inventoried due to lack of other elementary flows. Considering the type of processes concerned, it can be assumed that the error introduced is relatively small. Since the main impact assessment methods applied in this study are not considering water and soil emission at all, there is no influence whatsoever on the results of this study. More problematic is the fact that composition data for some of the fuels lack sulphur content while this is known for other fuels. This leads to a bias in the results in favour of the fuels with the least information

available. The issue is treated by an estimation of sulphur contents in the cases where no data is available. Emissions are calculated from these estimates and used for sensitivity analysis. Data quality for aluminium production which is used for comparison is also very high but not specific for various production methods.

Results and conclusions are mainly based on GWP which introduces a major limitation especially in the final comparison of magnesium components versus aluminium components. The other impacts discussed are based on the CML 01 method which, according to its authors is to be seen as outdated. However, CML's methods for calculation of acidification and eutrophication, the two impact categories chosen in the study, are not significantly different from the methods proposed in the new ReCiPe framework. The justification given for the choice of the characterization methods could have been better elaborated in the report, especially for part 4 where a comparative assertion is made and only GWP is used. This limitation is mentioned several times throughout the report but additional stress on limitations in the conclusion chapter would have been desirable. Also a dedicated chapter on limitations would have added value to the report. It could have mentioned the limitations in impacts covered but also the limited validity of the cradle to cradle results which are strictly speaking only applicable to the very specific components in very specific vehicles used in specific applications. Here, a discussion of how important these restrictions are could have helped the reader in extrapolating results to other components or situations.

Calculations of overall results (including use in vehicles) are made in Excel, based on LCIA results. This is not strictly in line with ISO 14'044 but it can be regarded as a "modular LCA" as described in ISO 14'025. Therefore, and since the results are not affected, this derivation from the standard procedure poses no problem at all.

In conclusion it can be said that the study and its documentation comply with ISO 14'044 in all relevant matters.