Assessment of Greenhouse Gas Emissions of Magnesium Use in Transport

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Introduction

Mitigating the impacts of climate change is one of the major challenges the world faces today. Thus, reducing greenhouse gas (GHG) emissions is one of the major tasks for all economic sectors. Due to a growing mobility demand worldwide, the transport sector is responsible for an increasing share of such emissions. There are different approaches for reducing the environmental impact from this growth. From a technical point of view, lightweight design is one key measure to increase the efficiency of different means of transportation. One promising lightweight material is magnesium, which can be used for many transport applications.

For the evaluation of the ecological benefits of lightweight design with magnesium, the entire lifecycle of such products has to be considered in order to reveal potential trade-offs between individual lifecycle stages. This article presents the results of an analysis of exemplary magnesium components in a passenger car and a mid-haul aircraft. The primary magnesium production, the manufacturing of the components, the use stage, and the recycling of the passenger car components are included in the evaluation. Though the analysis of potential environmental burdens is supposed to cover various categories, like effects on climate change, potential acidification and eutrophication effects, metal depletion, and others, this article focuses on the presentation of the development of GHG emissions as an indicator for effects on climate change.

Methodology and Definition of Goal and Scope

The lifecycle assessment (LCA) of magnesium presented in this article includes the entire lifecycle of two exemplary use cases: a steering wheel frame for use in a gasoline passenger car as well as a gearbox and a seal closer for both the top and bottom of a mid-haul aircraft door. In both examples, primary magnesium and alloy production, the manufacturing of the components, as well as the use over a certain lifetime of a car and an aircraft are considered. The steering wheel is produced in a die casting process, while the aircraft parts are manufactured via sand casting. In the case of the steering wheel frame, the end-of-life and a possible recycling path are part of the analysis. For the aircraft parts, the end-of-life is of minor importance and is not included in this evaluation. The assessment aims to analyze potential benefits of the use of magnesium compared to aluminum and to identify the main influencing factors for both applications in terms of potential environmental burdens.

Regarding the production of primary magnesium, recent technology developments and alternatives have been evaluated. For magnesium production via thermal reduction, a lifecycle inventory for the Pidgeon process in China was developed. The data represent an average Pidgeon process in China in the year 2011. Given the fact that more than 80% of the primary magnesium worldwide stems from Chinese Pidgeon process, the results represent the majority of magnesium available on the global market. Further, the production of primary magnesium in an electrolysis plant has been analyzed.

The focus of this study is the assessment of the analyzed product systems according to their contribution to the global warming potential. All emissions that are relevant for the greenhouse effect are calculated as kg carbon dioxide equivalents (CO_{2eq}) by using specific characterization factors.

Primary Magnesium Production

Description of the Product System: All processes of the magnesium lifecycle have been modeled with up-to-date data. Figures on energy and material consumption as well as process specifications of the Pidgeon process are primary data. In 2011, all producers used gaseous fuels as energy carrier for the production process. There are four gases in use: semi-coke oven gas, coke oven gas, producer gas (also known as generator gas), and natural gas. Unlike some years ago, coal is only used in the calcination step and not in any other process steps of the Pidgeon process. The most common gas is semi-coke oven gas, which is used for the production of 45% of the annual magnesium output in China. Another 34% of the magnesium is produced by using producer gas and 14% by using coke oven gas. Only 6% of the annual magnesium production is based on natural gas as an energy source. For the calculation of the material flows, data on most of the background processes like electricity production or the production of ferrosilicon (FeSi), which is consumed in considerable amounts, are country specific.

Assumptions on allocations are made for the production of coke oven and semi-coke oven gas. Emissions from the production of these gases are allocated to all products of this process (coke, coke oven gas, and tar) according to the energy content of each product. In China, coke oven and semi-coke oven gases are treated as waste from the coke and semi-coke production and both gases are given for free to magnesium producers. Thus, a second scenario has been calculated where the avoided emissions from unused waste gases are credited to the Pidgeon process.

The model on electrolysis is based on site-specific figures for a magnesium plant in Israel, especially in terms of energy consumption and cover gas utilization. Carnallite is the raw material for the magnesium production. The energy supply is based on natural gas. The cover gas used in the plant is the hydrofluorocarbon R135a. Apart from magnesium as the main product, the electrolysis plant produces liquid chlorine (Cl_2) and potassium chloride (KCl). Both by-products can substitute equivalent commodities from other production routes. The saved emissions from these other productions are credited to the electrolysis process in an additional scenario.

The results of the analysis are shown hereafter and refer to 1 kg of pure magnesium as reference flow.

GHG Emissions from Primary Magnesium Production: Based on the calculation of the material and energy flows of the Pidgeon process, as well as for all upstream processes needed for the supply of raw material and energy, the GHG emissions are calculated in terms of CO_{2eq}. Figure 1 depicts the average results of GHGs of the single process steps of the Pidgeon process and the total amount of 25.8 kg CO_{2eq}. The emissions from the upstream pro-

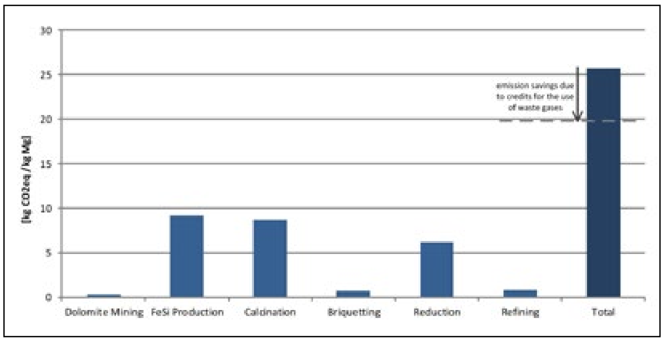

Figure 1. GHG emissions from the Pidgeon process.

cesses are allocated to the single process steps. Due to its energy intensive production, FeSi contributes considerably to the overall emissions from magnesium production. The reduction process has been subject to technical improvements during the past years, which leads to notably lower emissions compared to former analyses.[1-3]

The use of coke oven and semi-coke oven gas is driven by economic incentives and legal requirements, as both gases can be seen as waste from coke and semi-coke production. When crediting the use of these gases to the Pidgeon process, the weighted average emissions of the Pidgeon process drop to 19.9 kg CO_{2eq}.

The results for the GHG emissions from the electrolysis process are shown in Figure 2. The main contributor to these emissions is the consumption of energy that amounts to 94% of the overall emissions. As the electrolysis step itself consumes most of the energy, it is the main CO_{2eq}-emitting process step. Though R134a is a potent GHG, its influence on the results is comparatively low.

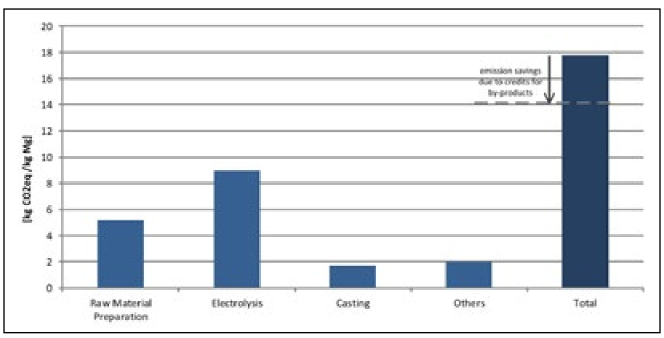

Figure 2. GHG emissions from the electrolysis process.

The by-products of the electrolysis (Cl_2 and KCl) substitute equivalent products from alternative production routes. This substitution can be credited in terms of saved GHGs from these alternative production systems. Considering these credits, the overall emissions of the electrolysis process decrease to 14 kg CO_{2eq}.

LCA of a Steering Wheel Frame Used in a Passenger Car

Description of the Product System: The use of lightweight materials in transport potentially leads to fuel reductions and lower emissions to the environment during the use stage. In order to evaluate possible advantages of the use of magnesium in passenger cars, a steering wheel frame made from magnesium is compared to one made from aluminum. The weight of the magnesium part is 0.55 kg and it is made of AM50. The aluminum part weights 0.74 kg and is made of $AlMg_3$. The exemplary use case refers to a mid-size gasoline passenger car with a mileage of 200,000 km. The calculation of fuel savings is based on a fuel reduction value of 0.35 liters per 100 km and per 100 kg. Both steering wheel frames are made from primary metal that is alloyed and then formed in a die casting process.

After its use, the metals are recovered after the treatment of the end-of-life vehicle. The light metals are not further separated, but sold to the market for secondary metals. Which is to say that the magnesium contained in the end-of-life vehicle ends up in the aluminum lifecycle as an alloying element. We assume, that both aluminum and magnesium substitute primary metal in their second life. This substitution is credited in terms of saved GHG emissions.

Manufacturing via Die Casting: The steering wheel frame analyzed was produced via die casting. In the case of magnesium, the use of a cover gas is necessary in order to prevent oxidation in the magnesium melt. There are three different gas types that can be seen as typical protection agents: SO_2/air mixture, SF_6/air mixture, or R134a/CO_2 mixture. Though all of these cover gases are used in practice, the use of SO_2 is seen as most representative. The consumption of cover gases is based on data from the EPA.[4]

Energy consumption for alloying and die casting are assumed to be equal for both metals, as both materials have similar melting points. In both cases, a certain amount of production scrap needs to be recycled. The magnesium scrap usually requires a separate recycling step, which in this example is modeled as an in-house solution with a separate furnace. The aluminum scrap is remelted directly.

Regarding the overall GHGs from the die casting process, magnesium shows lower emissions, when SO_2 or R134a are used as cover gas. Figure 3 shows the contribution of cover gas use, energy consumption, and material transport to the overall GHG emissions of the die casting process. Due to its greenhouse potential, the use of SF_6 dominates the evaluation of potential effects on climate change. For all other cover gas scenarios, as well as aluminum die casting, the consumption of electricity is most important for the GHG balance.

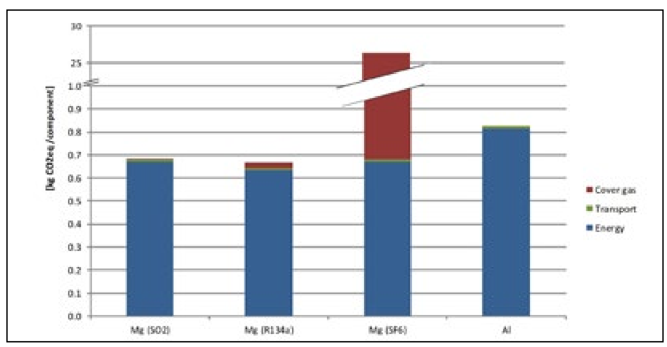

Figure 3. Contribution of cover gas, energy, and transport to the GHG emissions from the die casting process.

GHG Emissions from the Overall Lifecycle: Due to the high emissions of CO_2 from combustion engines, the use stage considerably influences the GHG balance of the entire lifecycle of a passenger car component. In the following, the differences of the absolute emissions of the lifecycle of both alternative steering wheel frames are analyzed. The lifecycle includes the production of the primary metal and its alloy, the die casting process, the use stage, and the end-of-life treatment and recycling of the metals. The net differences of the CO_{2eq} emissions between the magnesium and the aluminum component are shown in Figure 4. The emissions of GHG from a world average primary aluminum production is taken from Gao, et al.[5] During the use stage, the GHG emissions are reduced by 3.8 kg, when magnesium is used.

When the primary magnesium used for the component stems from the electrolysis process, less GHGs are emitted already during the production stage. This applies to

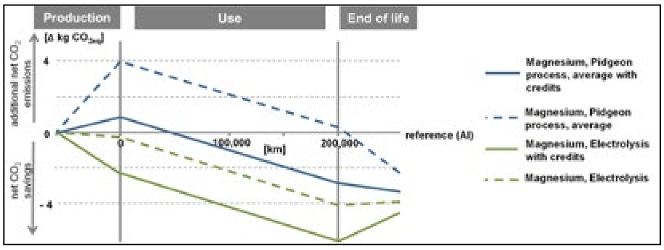

Figure 4. Net difference of GHG emissions of the magnesium steering wheel frame compared to the aluminum alternative.

both electrolysis scenarios with and without credits for the by-products of this process. In the case of magnesium produced by the Pidgeon process, the emissions from the production stage are higher than for the aluminum alternative. Crediting the use of waste gases (coke oven and semi-coke oven gas), as explained previously, leads to a break-even point of 46,000 km. At this distance, the higher emissions of the production stage are amortized by the emission savings during the use stage. For the average Pidgeon process without credits, the break-even point cannot be reached within the use stage, but net savings result from the end-of-life stage. For both metals, the substitution of primary metal is credited because of the recovery of materials at the end of the steering wheel lifecycle. The credits are given according to the origin of the magnesium in each scenario shown in Figure 4 and have a notable influence on the overall GHG comparison.[6]

LCA of Aircraft Components

Description of the Product System: Compared to road transport, aviation is even more sensitive to weight reduction because of the high energy demand and mileage of aircraft. The use case for aircraft parts refers to a mid-haul aircraft and a flight over a distance of 4,100 km. The emission savings are calculated for this specific flight. As component examples, three parts of an aircraft door are analyzed: a gearbox and a seal for the top and bottom. The parts are produced in a sand casting process. The recycling of the end-of-life parts is not included in this analysis.

Like in the passenger car example, the use of the magnesium parts is compared to aluminum parts with equal function. The magnesium parts are made from AZ91E, the aluminum parts from A356. The weight of the magnesium parts is 6.63 kg, while the aluminum parts weigh 8.5 kg. The overall weight saving for the entire aircraft amounts to 5.8 kg. The fuel savings of one reference flight is 4.7 kg of jet fuel.

Manufacturing via Sand Casting: The data for the sand casting process of the aircraft door parts are site specific for the production of such magnesium parts. The amount of production scrap is assumed to be equal for magnesium and aluminum. The sand casting process produces a certain amount of melt residue of which 89% is recycled. Unlike in the die casting process, the molds for the casting have to be formed for each part separately. Patterns are filled with a mixture of sand, binding materials, and an inhibitor that prevents the magnesium from reacting with the sand. This mixture is then compressed in a forming machine. The sand mold is filled with SO_2 and air in order to reduce the reactivity of magnesium in the mold. Finally, the alloy is melted and poured into the sand molds. In a further treatment step, the parts are cut into shape and powder coated. In the case of part production with aluminum, there are no inhibitor agents or protection gases needed in the process.

Figure 5 depicts the results for the GHG balance according to the contribution of the process steps. The overall emissions from the magnesium processing are lower than in the aluminum case due to the lower amount of material that has to be treated. For the production of the magnesium parts, the forming of the sand molds has a considerable influence due to the use of chemical agents. The main influencing factor for the sand casting itself is the comparatively high energy consumption.

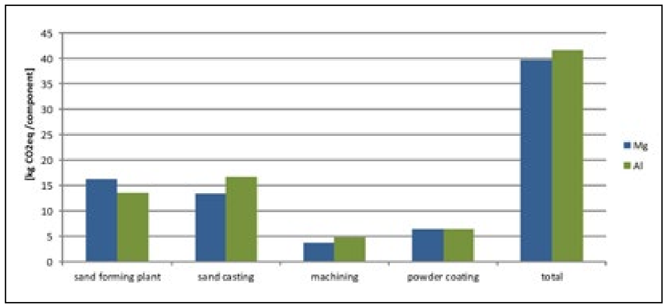

Figure 5. Contribution of the single process steps to the GHG emissions from the sand casting process.

GHG Emissions from the Overall Lifecycle: The GHG analysis for the comparison of aircraft parts from magnesium and aluminum is calculated on the basis of the reference flight. Only a few flights are necessary to reach the amortization of higher emissions from the production stage (Figure 6). The emissions from the component production stage using magnesium from the average Pidgeon process without any credits are amortized during the eighth flight. The emissions from the production stage are even lower compared to the aluminum alternative, when magnesium from the electrolysis process is used and the credits for by-products are included.

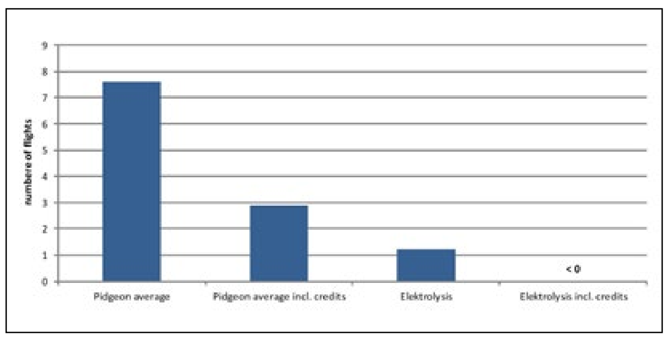

Figure 6. Number of reference flights needed for emission amortization for different magnesium scenarios.

The benefits of weight saving in aircraft operation are considerable. Given an annual mileage of 1.9 million km for an average mid-haul aircraft, the savings of GHGs due to an analysed weight difference of only 5.8 kg amount to approximately 8 tons. Assuming a lifetime of 30 years, the emissions per aircraft could be reduced by 226 tons CO_{2eq}.

Conclusion

The analysis of the primary magnesium production shows that the Pidgeon process has improved notably in terms of energy efficiency during the past years. Main influencing factors are the technical improvement of the reduction process and the use of fuel gases instead of coal. Compared to former studies, the electrolysis process shows a reduction of GHG emissions as well. The use of electricity based on natural gas instead of oil and the use of the cover gas R134a instead of SF_6 are the key factors for this reduction. Emissions could be further decreased by using a more efficient electricity production or renewable energy.

In the case of the manufacturing of components, the use of protective agents has a major influence on the emission of GHGs and on the comparison to the processing of aluminum. The analysis shows that there are common alternatives to SF_6 in use, which lead to a significantly lower effect on the climate. Another lever is the reduction of production scrap that could be decreased by technical or design improvements. Although most of the scrap from the casting processes is reused, the processing of additional material causes a higher energy and material consumption and hence leads to higher emissions.

The two use cases analyzed in this study indicate that the use of magnesium is beneficial in terms of GHG savings over the entire lifecycle. The sources of primary metal influence the balances significantly, when magnesium and aluminum are compared. The results for the passenger car example are more sensitive to assumptions on fuel efficiency and the characteristics of the product system than in the case of the aircraft example, as the mileage of passenger cars is comparatively low compared to other means of transportation. Nonetheless, the analysis of magnesium use in transport shows that this metal offers considerable potentials for GHG savings in transport.

Acknowledgements

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