Life Cycle Assessment of a New Pidgeon Process – KAR MİNERAL Summary of Results

Prepared for:

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MİNERAL MADENCİLİK

Title	Life Cycle Assessment of a New Pidgeon Process – KAR MİNERAL
	Summary of Results
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1   Goal and Scope of Study

The Pidgeon process has become the dominant production path for primary magnesium during the last fifteen years. The process was invented in Canada in the 1940s, but in recent years has been used almost exclusively in China, which covers about 88 % [1] of current world production. In 2012, KAR MİNERAL started to build up a magnesium production plant using the Pidgeon process technology in Cifteler, Central Turkey. This study is based on planning data from the KAR MİNERAL plant. The aim is to assess the potential impacts of emissions from the plant and the upstream processes with a focus on greenhouse gas emissions. The study identifies hot spots for emissions and resource consumption as well as potential solutions for lowering emissions from the overall process chain.

The functional unit of the study is 1 kg of pure magnesium produced via the Pidgeon process and a final refining step. The analysis follows a cradle-to-gate approach and includes all upstream processes. The energy and material supply for the core processes are site-specific and are modelled according to the geographic location of the processes. Figure 1 gives an overview of the basic idea of the KAR MİNERAL LCA study. Detailed information on the data used and the results of the impact assessment are given below.
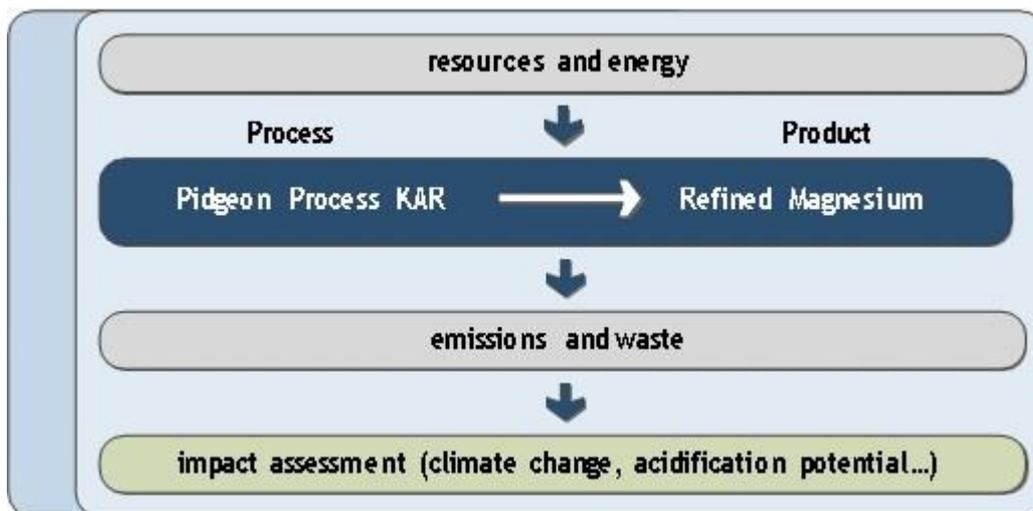

Figure 1: Overview of the KAR MİNERAL study

2 Process Data from Primary Magnesium Production at KAR MİNERAL

In this study, the data for the core processes at KAR MİNERAL is site-specific and reflects the planning status of the plant. Figure 2 gives an overview of the processes included. Each process needs raw and operation materials as well as energy, which are produced in upstream processes.

The dolomite as a raw material for magnesium production comes from a mine owned by KAR MİNERAL which is located near (300m) the magnesium plant. The dolomite mining process has been modelled according to KAR MİNERAL -specific data. The production of the ANFO[1] explosive has been modelled according to its composition and complemented by data from a similar explosive. The energy supply for the mining process is represented by the Turkish grid mix and a generic diesel production.

The Pidgeon process itself consists of three main steps: calcination, preparation of briquettes, and reduction. In the calcination phase, the carbon dioxide (CO_2) is released from the crystal lattice of the dolomite by heating the material in continuously rotating furnaces. The material is then ground into fine powder and mixed with the reaction agents ferrosilicon (FeSi) and calcium fluoride (CaF_2). The mixed material is then pressed into briquettes. The magnesium is produced in the reduction furnace, where it evaporates at high temperatures. The resulting magnesium crowns are treated in a final refining step in order to produce pure magnesium ingots. The efficiency of this process is assumed to be 98%. A lower efficiency of 93% has been considered in a sensitivity calculation. In the refining step, a cover gas must be used to protect the magnesium from oxidation. KAR MİNERAL uses sulphur dioxide (SO_2) for this purpose.
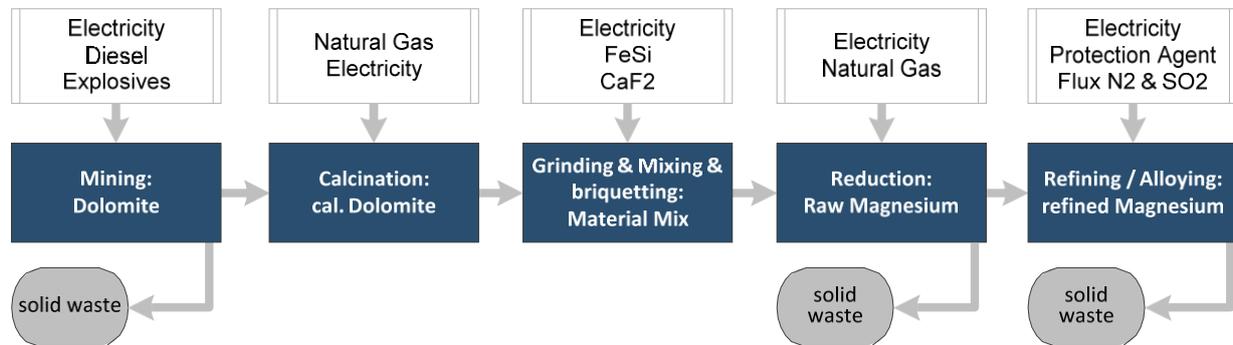

Figure 2: Overview of the Pidgeon process steps incl. refining

The emissions from the pure magnesium production process have been calculated for all main and upstream processes. The main input parameters were provided by KAR MİNERAL and are listed in Figure 3. One main factor influencing the energy consumption of the Pidgeon process is the consumption of FeSi, which is highly energy-intensive to produce. FeSi production has been modelled according to the process described in the IMA LCA study [2] (Figure 4). The KAR MİNERAL plant uses FeSi purchased from Russia and Asia. In the model, both options are represented with a share of 50%. An alternative supply has been modelled in

[1] ANFO (ammonium nitrate fuel oil) consists of 94% ammonium nitrate as an oxygen carrier and 6% fuel oil as a carbon carrier.

a dedicated "adequate FeSi sourcing" scenario. In this scenario, the FeSi production is characterized by an electricity mix of 75% water power and 25% natural gas generation.
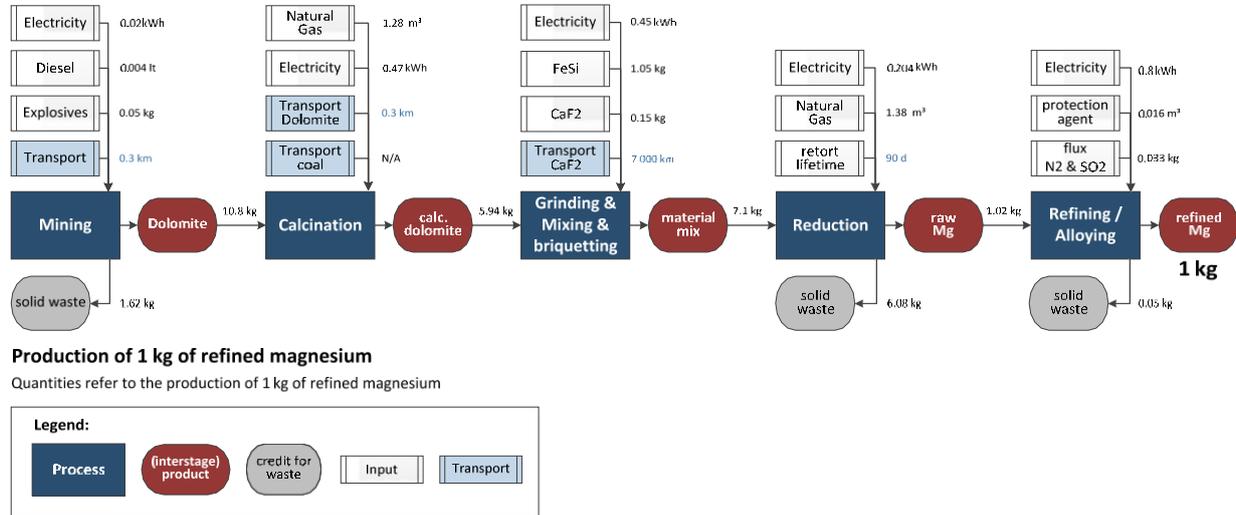

Production of 1 kg of refined magnesium
Quantities refer to the production of 1 kg of refined magnesium

Figure 3: Input materials, energy flows and solid waste amounts of the main process steps
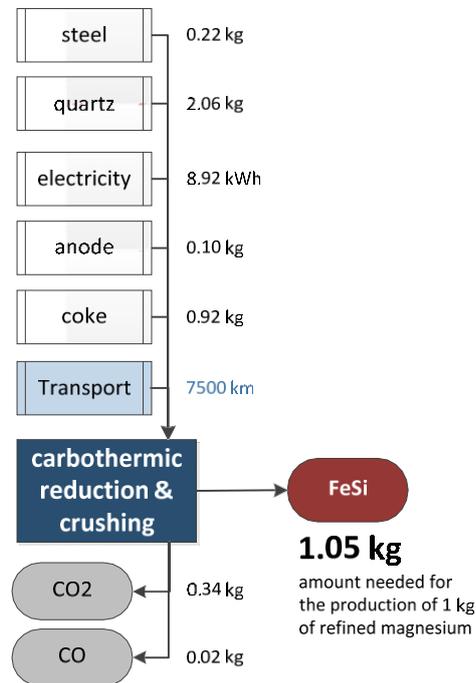

Figure 4: Input materials and energy for FeSi production

The electricity mixes for Turkey and other relevant countries have been adapted to the latest available status as given in [3]. The electricity supply of the magnesium production plant itself is provided by the Turkish grid, a cogeneration plant run on natural gas and solar power. This KAR MİNERAL electricity mix for the baseline scenario is 55% grid, 30% cogeneration and 15% solar. Alternative scenarios with various electricity mixes have been calculated.

The natural gas supply for the KAR MİNERAL plant has been modelled according to the gas import statics for Turkey [4]. The main source of gas supply is Russia with 58 % [4] . Due to a lack of data for the upstream processes, the natural gas supply in this study has been divided into two groups: import from Russia, which represents all gas imports via pipeline, and import from Algeria, which represents all liquefied natural gas (LNG) imports. These processes, as well as other material and energy consumptions of the upstream processes, are taken from the ecoinvent 3.1 database.

The flows of materials and energy to and from the environment were calculated using the Umberto 7.1 software program. These "elementary flows" were evaluated using the Recipe impact assessment method [5]. The main focus of this study is to evaluate effects on climate change expressed as global warming potential (GWP). All emissions relevant for the greenhouse gas effect are calculated as carbon dioxide equivalents (CO_{2eq}). The GWP of each gas is calculated in relation to CO_2 and for a time horizon of 100 years. Methane (CH_4), for instance, has a GWP of 25 CO_{2eq}. The Recipe method includes 17 other categories. This study assessed the acidification potential as well as particulate matter formation and fossil resource depletion, as these are the most relevant impact categories for this type of process. Due to the high level of uncertainty, no assessment of NO_x emissions in terms of potential eutrophication was conducted.

In addition to emissions, some of the processes also produce solid waste. The waste from dolomite mining can be used in the glass industry or as road construction material. The slag from the production process can be used for cement production. Thanks to the magnesium content of the refining slag, this waste can be used as primary magnesium substitute in the steel industry. When these solid wastes replace other primary materials in other industries, these other primary materials do not have to be produced. As a result, using the solid waste materials has the potential to save emissions, which could then be credited to the KAR MİNERAL primary magnesium production process.

3 Impact Assessment of Primary Magnesium Production at KAR MİNERAL

3.1 *Assessment of Global Warming Potential*

The analysis of the Pidgeon process at KAR MİNERAL results in overall GHG emissions of 23.6 kg CO_{2eq} per kg magnesium ingot. The contribution of the energy supply, the raw material supply and the process itself is depicted on the left-hand side of Figure 5. The energy supply in this figure refers exclusively to the energy consumption of the Pidgeon process steps and the refining process. The production and transport of the natural gas used to heat the calcination and reduction furnaces has a considerably higher impact than the electricity supply. The raw material supply is dominated by the FeSi production process and the high proportion of fossil-fuel-based electricity in the countries of origin. In the Pidgeon process, the main contributors are the emissions from the CO_2 release during calcination and from the combustion of natural gas for calcination and reduction. This is also reflected on the right-hand side of Figure 5, which shows the contribution by process step. The FeSi production process is attributed to the briquetting step as the material enters the process at this stage. FeSi production exceeds the contribution from other steps and represents 41% of overall emissions.
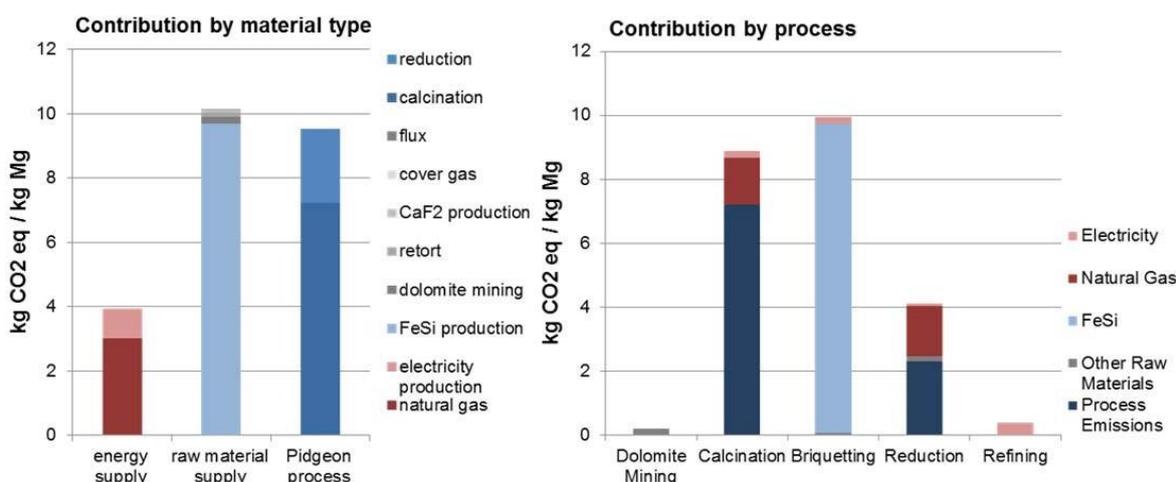

Figure 5: Greenhouse gas emissions from the KAR MİNERAL Pidgeon process plant

The solid waste materials from the process steps can be re-used for different purposes as described above. Table 1 lists the amount of process waste and the possible GHG credits per waste. The maximum possible credit would be 3.3 kg CO_{2eq}. The main contribution comes from replacement of blast furnace slag in cement production which shows a high uncertainty. The final amount of potential credits can be determined when the plant is running and the wastes are sold to other industries. If the slag from the reduction process needs to be landfilled, additional GHG emissions of up to 2.6 kg CO_{2eq} could be caused, depending on the composition of the magnesium slag.

Table 1: Amount of solid waste per process and potential GHG credits

Waste	Amount [kg / kg Mg]	Substituted Material (data from ecoinvent 3.1)	GHG Credit [kg CO2eq / kg Mg]
solid waste from dolomite mining	1.6	gravel or silica in road construction	0.02
		dolomite in glass industry	0.03
slag from reduction process	6.1	ground granulated blast furnace slag in cement production	2.2 - 3.0
		crushed limestone in cement production	0.02
slag from refining process	0.1 (11% Mg content)	primary Mg from CN in steel industry	0.3

As the results of the study are based on planning figures, some of the process parameters are subject to change when the plant is running on an industrial scale. As the energy consumption of the FeSi production contributes considerably to the GHG emissions in the baseline scenario, an alternative FeSi supply with a higher share of renewable energy would lead to a notable reduction of overall GHG emissions of 6.9 kg CO_{2eq}. Together with the credits for the use of the solid waste materials, this scenario would result in an overall GHG balance of 13.3 kg CO_{2eq}/ kg Mg. In the experience of KAR MİNERAL , the consumption of FeSi in the Pidgeon process could also be reduced. The minimum FeSi consumption would be 0.54 kg per kg magnesium. This would save 4.7 kg CO_{2eq} with the same FeSi sourcing as in the baseline scenario. The "adequate FeSi sourcing" scenario combined with the lower FeSi consumption leads to about 12 kg CO_{2eq} including the credits for waste use (Figure 6).
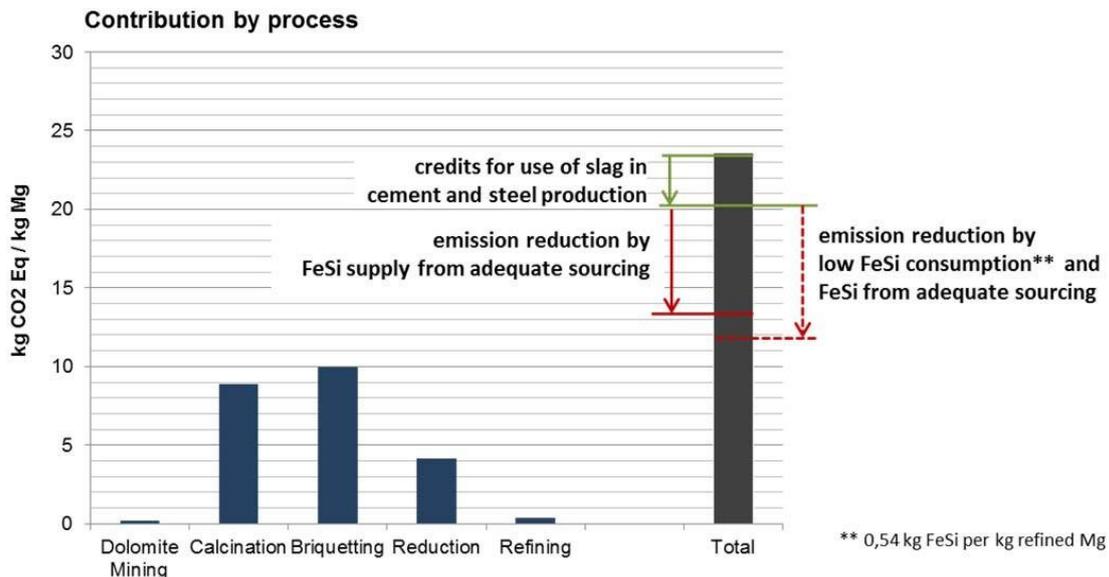

Figure 6: Greenhouse gas emissions from the KAR MİNERAL Pidgeon plant – overview with scenarios (variation of FeSi parameters)

Further scenarios and sensitivities have also been evaluated. Varying the electricity mix has a minor influence on the overall GHG balance (Table 2). A less efficient refining step would lead to higher energy and material consumption per kg magnesium ingot in the overall process chain and would result in an increase of 1.2 kg CO_{2eq}. The greatest influence can be achieved by switching FeSi supply and reducing FeSi consumption as described above. All of the absolute GWP results in Table 2 have been calculated without deducting the credits for the use of solid waste materials.

Table 2: GWP results for alternative scenarios and sensitivities

Scenario	Absolute GWP [kg CO2eq / kg Mg]	Description
Basis	23.6	KAR MİNERAL electricity mix: 30 % cogeneration plant, 55 % Turkish grid, 15 % photovoltaic
Adequate FeSi sourcing	16.7	100 % supply with a share of 75 % water power for the electricity production
Low FeSi consumption	18.9	FeSi ration 0.54
Low FeSi consumption and adequate sourcing	15.3	FeSi ration 0.54 and supply with a share of 75 % water power for the electricity production
45 % solar energy	23.2	KAR MİNERAL electricity mix: 55 % cogeneration plant, 45 % photovoltaic
Alternative electricity mix	23.5	KAR MİNERAL electricity mix: 55 % cogeneration plant, 30 % Turkish grid, 15 % photovoltaic
Low efficiency	24.8	Pure Mg yield in the refining step is 93 %

The GWP performance of the KAR MİNERAL process shows lower emissions than an average Pidgeon process in China (Figure 7) and is at about the same level as the most efficient plants in China. The existing electrolysis plant in Israel shows lower GHG emissions thanks to more energy-efficient electrolytic processes.

Nevertheless, the analysis of the KAR MİNERAL Pidgeon process shows that the emissions level of electrolysis can be achieved when the solid waste materials replace other products and the FeSi consumption and / or sourcing is changed.
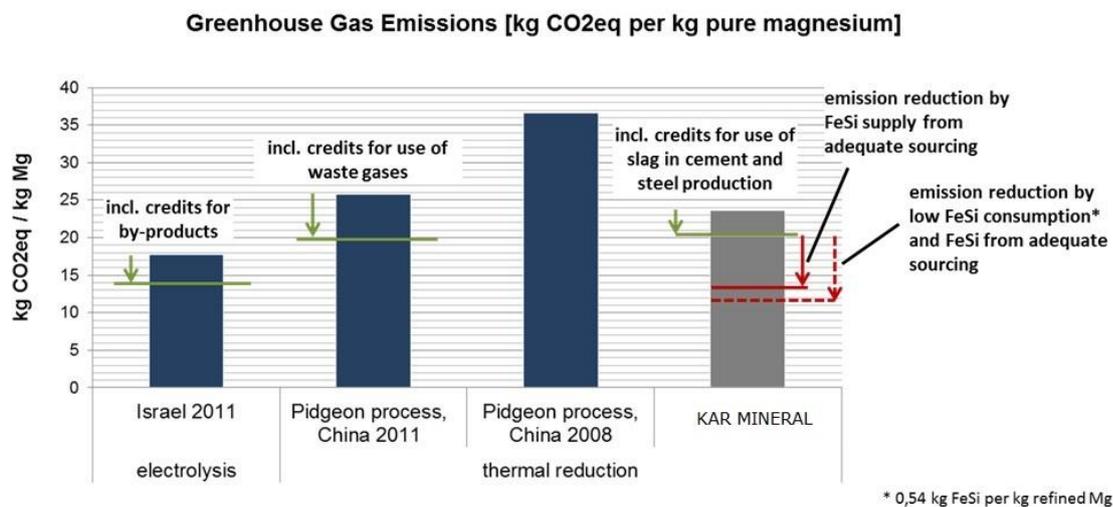

Figure 7: Comparison of different magnesium production routes (sources: [6, 7])

3.2 Further Impact Categories

The analysis of other impact categories shows that the use of fossil fuels for electricity production and for heating the furnaces in the Pidgeon process leads to emissions of GHG and other pollutants which exceed the emissions from other parts of the process chain (Figure 8). Regarding the SO_2 emissions, which contribute mainly to the acidification potential, the use of this gas as a cover gas shows only a minor influence as only a small amount of it is needed. The combustion of natural gas in the process most probably contributes much more to the SO_2 balance. The real emissions depend on the sulphur content of the natural gas used in the plant. In this study, the emissions from natural gas combustion are based on data from the IMA study [2]. Considering the current regulations on the concentration of pollutants in industrial waste gases, the SO_2 emissions might be critical if no exhaust gas treatment mechanisms are in place. However, this can only be assessed with data on real emissions when the plant is running, as the actual amount of waste gas is not determined in this study.

The level of NO_x emissions is determined by the combustion conditions in the furnaces. Estimations of the NO_x emissions from the Pidgeon process in China (which are presented in the IMA dataset of the ecoinvent database) point to 30 g per kg magnesium. The NO_x emissions should thus be further assessed under real process conditions. Emissions of particulate matter (PM) from the Pidgeon process are low thanks to the dedicated exhaust gas treatment process. Most of the PM emissions can be expected from the upstream processes of FeSi production.

The fossil depletion category shows that the consumption of the natural gas in the Pidgeon process has a higher impact on fossil resources than the electricity consumption of FeSi production, which is also dominated by fossil fuels. The electricity mix at the KAR MİNERAL plant has a small influence due to the comparatively low electricity consumption and partly due to the use of renewable energy.
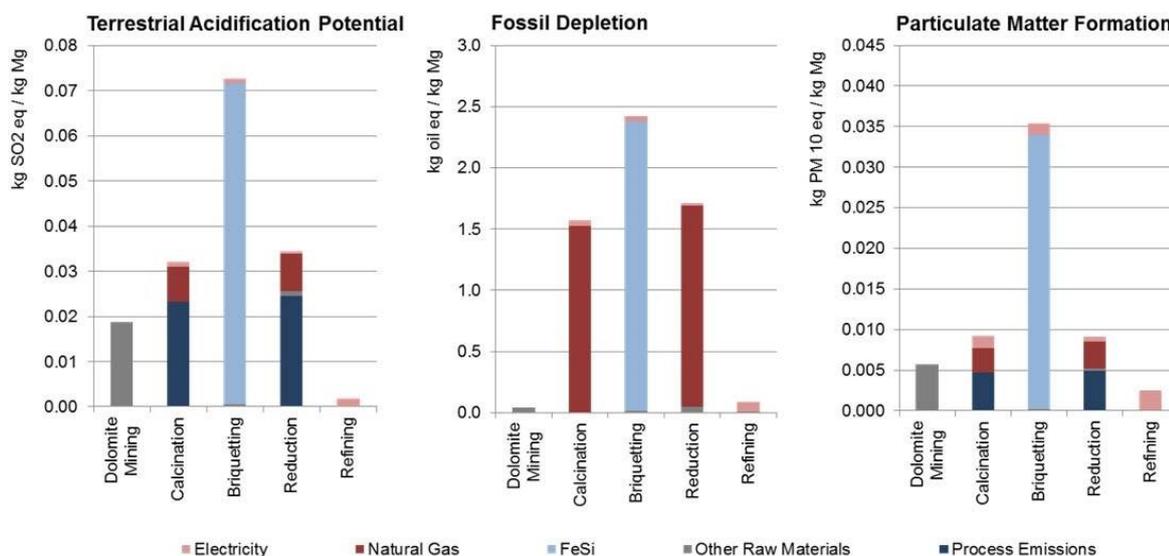

Figure 8: Results for further impact categories from the KAR MİNERAL Pidgeon process plant: terrestrial acidification potential, fossil depletion and particulate matter formation

4   Transport of Magnesium to Central Europe

The model of the KAR MİNERAL Pidgeon process includes the transport of raw materials to the production site. For the consumer of the primary magnesium, additional transport to the final destination is necessary. The actual emissions of the magnesium transport depend on the distance travelled, but also on the means of transport and specific factors such as vehicle types and the degree of capacity utilization. Nevertheless, a valid estimation of GHG emissions from transport can be made by analysing the probable transport distances. Table 3 shows the distances per means of transport for a probable transport route from the KAR MİNERAL plant to Central Europe. An example route for transporting magnesium from China to Central Europe is also given. The table shows the related GHG emissions, which are broken down into individual transport sections in Figure 9. Since the shipping distance is 10 times greater, the emissions from China are about twice as high as the emissions from the transport from Turkey.

Table 3: Transport distances and related CO_{2eq} emissions for production from the KAR MİNERAL plant and from China to Central Europe

Transport	Transport by ship		Transport by truck	
	km	kg CO_{2eq} /kg Mg	km	kg CO_{2eq} /kg Mg
KAR MİNERAL – Central Europe	1800	0.02	1750	0.18
China – Central Europe	20000	0.23	1500	0.15

Figure 9: GWP contribution from material transport to Central Europe

Greenhouse Gas Emissions [kg CO2eq per kg pure magnesium]
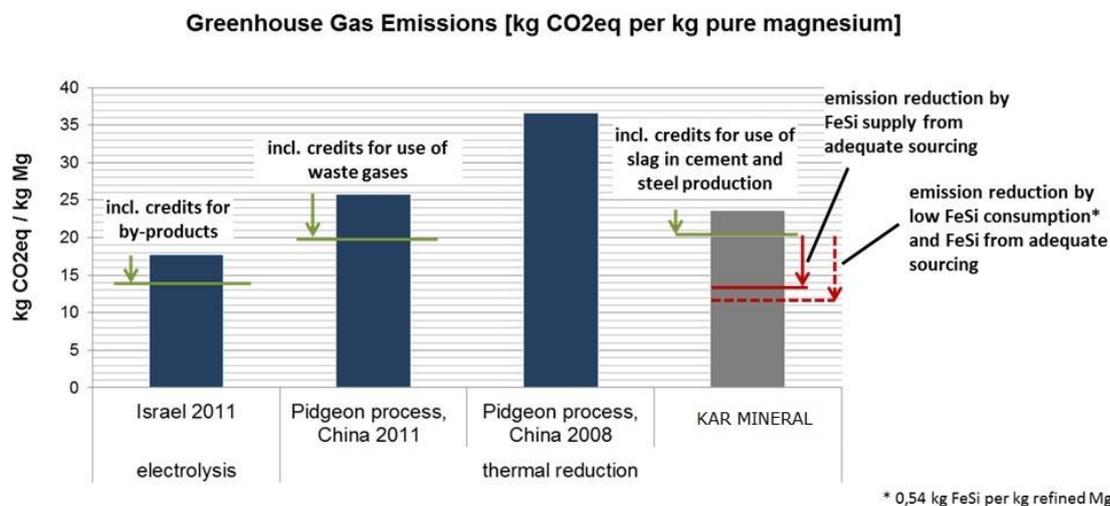
5   Conclusions

The study shows that the emissions from the KAR MİNERAL Pidgeon process are lower than from an average plant in China and are about the same as efficient Chinese Pidgeon process plants. The further use of the solid process wastes in other industries is beneficial and could be credited with up to 3.4 kg of CO_{2eq} depending on their final end use. Emissions could be lowered by reducing the use of FeSi or by using an alternative source which uses a higher share of renewable electricity. It would also be preferable to reduce consumption of natural gas, but this would have a lower impact compared to FeSi supply. This mechanism does not only apply to the GWP impact category, but also to other categories assessed, as the use of energy based on fossil fuel resources and the resulting emissions into the atmosphere have the most environmental impact. The direct emission of CO_2 from dolomite conversion in the calcination process step also has a notable contribution, but is unavoidable in this method of magnesium production.

Regarding the transport of the magnesium to the consumer, the location of the KAR MİNERAL plant has significant benefits for customers in Europe. It can be expected that the GHG emissions of material transport from the KAR MİNERAL plant are about half those of transport from China in the case of the representative transport routes considered in this study.

6   Sources

1.   USGS, *Magnesium Metal Statistics 2014*, in *Mineral Commodity Summaries*, E.L. Bray, Editor 2015.
2.   Ehrenberger, S., H. Dieringa, and H.E. Friedrich, *Life Cycle Assessment of Magnesium Components in Vehicle Construction*, 2013, German Aerospace Centre, Institute of Vehicle Concepts: Stuttgart. p. 109.
3.   OECD / IEA, *Electricity Information 2014 with 2013 data*, in *IEA Statistics* 2014, Paris.
4.   OECD / IEA, *Energy Supply Security 2014*, 2014: Paris.
5.   Goedkoop, M., et al., *ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; Report 1: Characterisation; First edition (Version 1.08)*, 2013, Ruimte en Milieu Ministerie van Volkshuisvesting.
6.   Ehrenberger, S., H. Dieringa, and H.E. Friedrich, *Life Cycle Assessment of Magnesium Components in Vehicle Construction*, 2013, Deutsches Zentrum für Luft- und Raumfahrt.
7.   Gao, F., et al., *Life cycle assessment of primary magnesium production using the Pidgeon process in China.* The International Journal of Life Cycle Assessment, 2009. **14**(5): p. 480-489.