Life cycle assessment baseline

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Upscale of Permanent Magnet Dismantling and Recycling – VALOMAG (19049)
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Content

1. Introduction

This report describes the baseline life cycle assessment (LCA) of a virgin Nd-Fe-B magnet production system, setting a benchmark for the for the recycling technology to be developed in VALOMAG project.

Given that virgin production of Nd-Fe-B magnets requires mining and processing rare-earth elements, which has several negative environmental impacts, there is great interest in creating technologies for recycling existing magnets which have a low environmental impact. The SUEZ, BRGM, CRM, Kolector and CEA partners in the VALOMAG project are in the process of scaling up their respective recycling processes and are interested in comparing their current and future recycling process with the baseline magnet production through LCA.

The recycling technologies under development are expected to have lower environmental impacts when comparing with virgin magnet production (Jin et al. 2018). A baseline of production can present the environmental impacts in different categories of primary magnets in each production process. The results from literature have shown that several environmental impact categories are related to the mining of ores needed for magnet production (Bailey et al. 2020).

2. Life cycle assessment methodology

2.1. Goal and scope

This baseline report assesses the life cycle impact of the primary NdFeB magnet production with life cycle assessment methodology. The report provides a reference for the recycling technologies in development in VALOMAG project. The LCA results of the baseline report will be compared with the results of the VALOMAG technologies at the later stage of the project.

We created the Life -Cycle Inventory with Activity Browser software, which is an open-source software GUI for modelling and performing LCA. We collected the foreground data (primary and site-specific data are used in an LCA) from the existing literature, which covers the entire production chain of NdFeB magnets, from mining to the production of the magnets, but not the incorporation of these magnets into the final products (Sprecher et al. 2014). The background system data is from the ecoinvent 3.6 dataset (Wernet et al. 2016).

The functional unit is the quantified function provided by the product system(s) , which is used as a reference basis in an life cycle assessment research (Guinée et al. 2002). The functional unit for this report is defined as the production of 1 kg NdFeB permanent magnet from ore mined in the Bayan-Obo mine of China.

The system boundary is shown in Figure 1. The processes included in this report are from mining to electroplating. The processes from mining to solvent extraction are the processes where ore mine turns into rare earth oxide. The other processes, from electrolysis to electroplating, are the processes where rare earth oxide are manufactured into NdFeB magnet. These two part are analysed respectively in the following chapter.

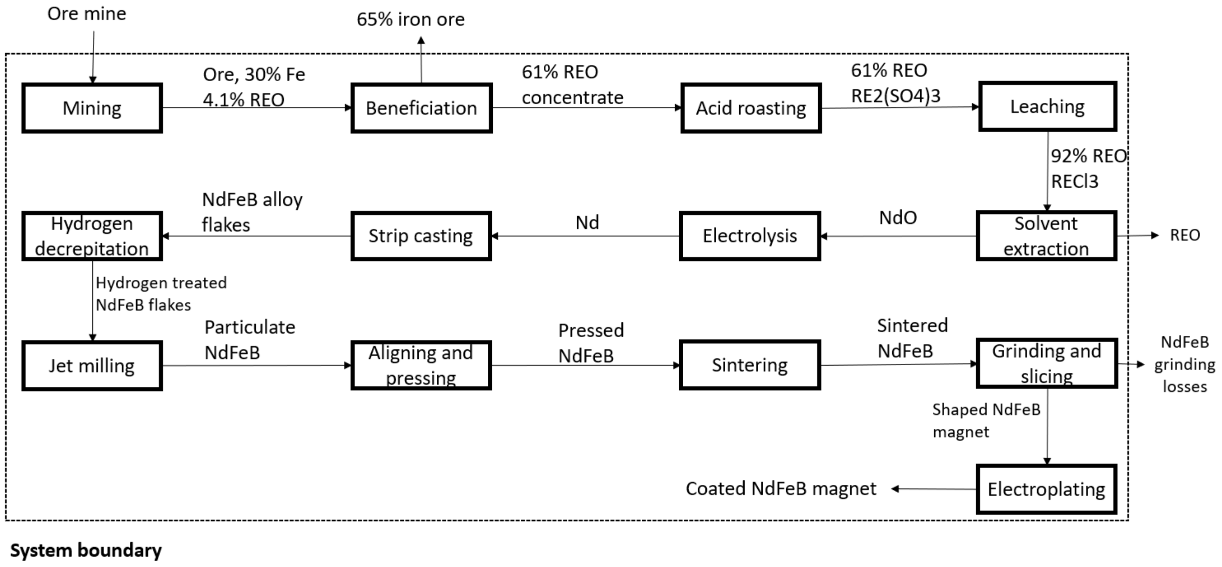

Figure 1 System boundary of the LCA baseline

2.2. Life Cycle Impact Assessment

Several specific impact categories were used to perform the life cycle assessment in the Activity Browser. These impact categories are: human toxicity, global warming potential, freshwater and terrestrial acidification, ozone depletion, ionising radiation, metal depletion, freshwater aquatic ecotoxicity, freshwater eutrophication and marine eutrophication.

Human toxicity

The impact category for human toxicity relates to the characterization of toxic chemicals relevant to human exposure. Emissions of arsenic, chromium, formaldehyde and cobalt to soil, air or water all have an impact on human toxicity. These various emissions are expressed as human toxicity through the reference unit kg 1,4-DC (Dichlorobenzene) equivalent.

Global warming potential

Many economic processes have an impact (positive or negative) on climate change which is expressed as the global warming potential. What this means is that the emissions from the process have a certain potential to cause global warming, these emissions include among others: Carbon dioxide, methane and ethane. The global warming potential of an emission is expressed over a certain time horizon, with the most commonly used being 100 years (GWP100). Global warming potential is measured using the unit 'kg CO2 equivalent'.

Freshwater & terrestrial acidification

Rising freshwater and terrestrial acidification is harmful to various aquatic and terrestrial organisms. Emissions of ammonia, nitrogen oxides and sulfur dioxide are factors in acidification. The impact on freshwater and terrestrial acidification is expressed in the 'mol H+ equivalent unit'.

Ozone depletion

Ozone depletion, similarly to global warming potention, is expressed over a given time horizon. All ozone depleting compounds are defined relative to the reference compound chlorofluorocarbon-11 (CFC-11) and expressed in 'kg CFC-11 equivalent' units.

Ionising radiation

This impact category refers specifically to all emissions that can ionize atoms or molecules by removing electrons from them. Long-term exposure in humans can lead to cancer. This impact category is expressed in the reference unit 'kg U235 equivalent'.

Metal depletion

The metal depletion impact category models the use of non-renewable metal resources or mineral depletion potential by expressing it with the reference unit 'kg Fe equivalent'.

Freshwater aquatic ecotoxicity

Freshwater aquatic ecotoxicity models the impact of toxic chemicals relevant to freshwater aquatic life over a given time horizon. Similarly to human toxicity, ecotoxicity is expressed in the reference unit kg 1,4-DC.

Freshwater and Marine eutrophication

Eutrophication describes the process whereby a body of water becomes enriched with minerals and nutrients. An excess of nutrients such as nitrogen or phosphorus will stimulate algal and aquatic plant growth, which can lead to drastic ecological changes in bodies of water. Freshwater eutrophication is expressed in the reference unit 'kg P equivalent', while marine eutrophication is expressed in 'kg N equivalent'.

3. Results

In this section, we present the LCA results of rare earth magnets. Based on previous literature and our research, nine impact categories are chosen for the baseline LCA in VOLAMAG project, which are human toxicity, climate change, freshwater and terrestrial acidification, ozone depletion, ionising radiation, metal depletion, freshwater aquatic ecotoxicity, freshwater aquatic ecotoxicity, freshwater eutrophication, and marine eutrophication. The total impacts of magnet production from mining are shown in Table 1. The impacts by process and by impact category are discussed respectively in 3.1 and 3.2.

Table 1: LCA results of NdFeB magnet

Impact category	NdFeB magnet
human toxicity (kg 1,4-DC.)	18.63
climate change (kg CO2-Eq)	23.50
freshwater and terrestrial acidification (mol H+-Eq)	0.43
ozone depletion (kg CFC-11.)	0.00
ionising radiation (kg U235-Eq)	1.74
metal depletion (kg Fe-Eq)	4.56
freshwater aquatic ecotoxicity (kg 1,4-DC.)	43.27
freshwater eutrophication (kg P-Eq)	0.01
marine eutrophication (kg N-Eq)	0.06

3.1. Impacts by process

Processes from mining to REO

To identify the sources of the different impacts, we further analyse the impacts of each process. For the REO production: Mining, beneficiation, acid roasting, leaching, and solvent extraction are included. Table 2 shows the impacts in nine different impact categories of each process, where we can easily locate the "hotspots" of each impact category. For example, human toxicity is mainly from acid roasting, which is almost 10 times as much as the second biggest source (leaching). Mining is the largest contributor to climate change, freshwater and terrestrial acidification, ozone depletion, ionising radiation, and marine eutrophication. This also supports the great potential of lowering environmental impacts from magnet recycling, which excludes the mining process. Metal depletion, freshwater aquatic ecotoxicity, and freshwater eutrophication mainly come from leaching process, which consumes hydrochloric acid in our modelling.

Table 2: LCA results by process of REO production

Impact category	mining	beneficiation	acid roasting	leaching	solvent extraction
human toxicity (kg 1,4-DC.)	0.51	0.87	22.70	2.30	1.77
climate change (kg CO2-Eq)	13.47	4.62	3.54	2.81	2.48
freshwater and terrestrial acidification (mol H+-Eq)	0.22	0.02	0.14	0.03	0.02
ozone depletion (kg CFC-11.)	2.32E-06	5.06E-07	4.59E-07	1.03E-06	1.25E-06
ionising radiation (kg U235-Eq)	0.88	0.54	0.29	0.64	0.48
metal depletion (kg Fe-Eq)	0.10	0.10	0.28	0.41	0.14
freshwater aquatic ecotoxicity(kg 1,4-DC.)	0.80	1.53	0.37	3.33	1.26
freshwater eutrophication(kg P-Eq)	2.60E-04	7.77E-04	1.75E-04	1.78E-03	6.98E-04
marine eutrophication(kg N-Eq)	0.093	0.005	0.005	0.005	0.003

Processes from REO to RE magnet

For the RE magnet production, we include electrolysis, strip casting, hydrogen decrepitation, jet milling, aligning and pressing, sintering, grinding and slicing, and electroplating. The impacts in nine different impact categories of each process are shown in Table 3. Electrolysis has the largest impacts on climate change comparing to other processes. And electroplating has a leading position in all the other eight impact categories. The high impacts of electroplating process mainly come from the Nickel coating.

When we compare total impacts of the REO production with RE magnet production, REO production has a much higher number on most of the impact categories. For example, even electroplating process shows a dominant impact in the REO to magnet production processes, but the total human toxicity of REO production process is almost five times as RE magnet production. For climate change, the first phase processes (REO production) contribute the two thirds of the whole production process (from mine to magnet). The second phase processes (from REO to RE magnet) show larger impacts on metal depletion and freshwater aquatic ecotoxicity, where Nickel coating contributes the most.

Table 3: LCA results by process of REO production

Impact category	**electrolysis**	**strip casting**	**hydrogen decrepitation**	**jet milling**	**aligning and pressing**	**sintering**	**grinding and slicing**	**electroplating**
human toxicity (kg 1,4-DC.)	0.63	0.25	0.05	0.43	0.09	0.69	0.18	3.53
climate change (kg CO2-Eq)	3.71	1.20	0.23	2.08	0.46	3.10	0.94	1.70
freshwater and terrestrial acidification (mol H+-Eq)	0.02	0.01	0.00	0.01	0.00	0.02	0.01	0.19
ozone depletion (kg CFC-11.)	4.1E-08	1.1E-08	1.6E-08	1.4E-08	3.2E-09	1.9E-08	3.3E-09	7.3E-08
ionising radiation (kg U235-Eq)	0.06	0.04	0.10	0.04	0.01	0.05	0.02	0.09
metal depletion (kg Fe-Eq)	0.02	0.07	0.00	0.01	0.00	0.02	0.01	3.94
freshwater aquatic ecotoxicity (kg 1,4-DC.)	0.89	0.48	0.07	0.66	0.15	0.88	0.30	36.66
freshwater eutrophication (kg P-Eq)	6.0E-04	3.4E-04	5.0E-05	4.5E-04	9.9E-05	6.0E-04	2.0E-04	2.5E-03
marine eutrophication (kg N-Eq)	0.004	0.002	0.000	0.003	0.001	0.004	0.001	0.004

3.2. Impacts by impact category

Climate change

Shown in Figure 2 are the relative process contributions towards climate change through global warming potential. The biggest contributor towards climate change are electricity-generating processes: high voltage electricity generation and diesel-electric generation for magnet production from different processes take up to more than 60%. Figure 3 is a part of the Sankey Diagram where the cumulative contributions to climate change of both the background (Ecoinvent 3.6) and the foreground data present. The top two contributors are electricity generation (42.9%) and REE mining (39.4%).

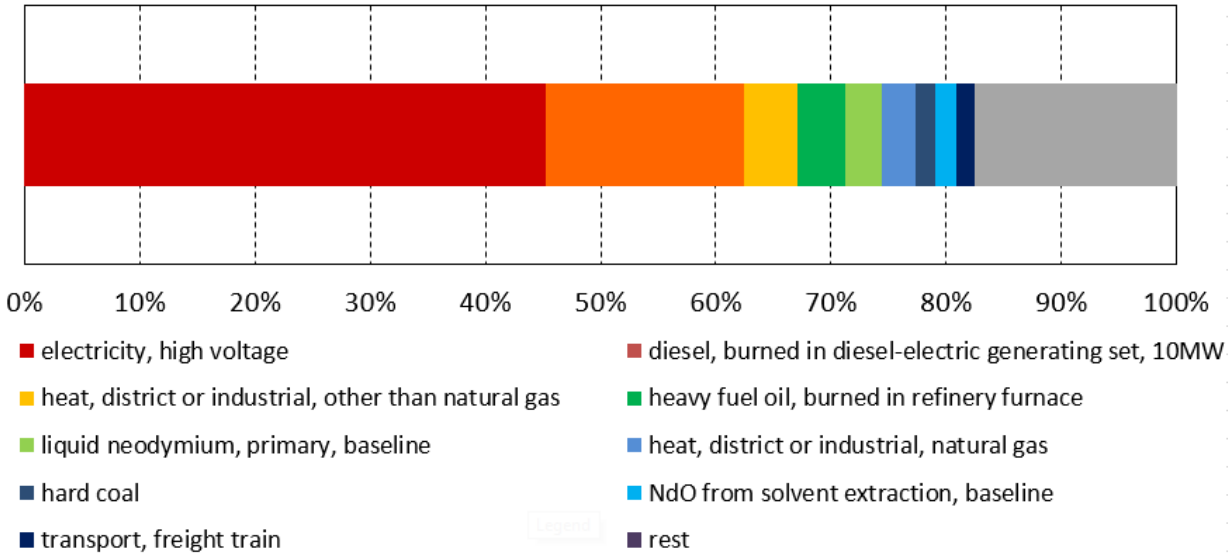

Figure 2 Process contributions to climate change (%)

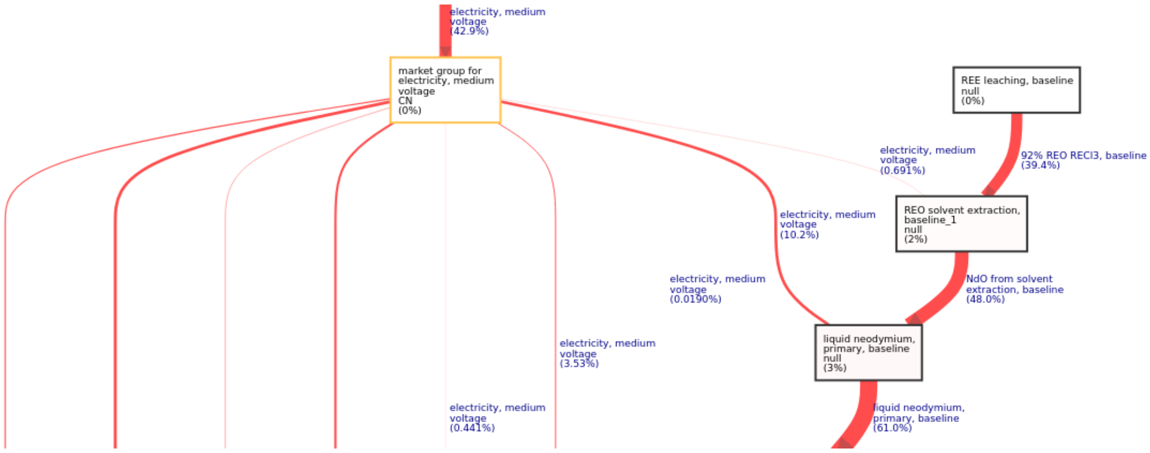

Figure 3 Process contributions electricity to climate change (%) in Sankey diagram

Human Toxicity

Figure 4 shows the relative impacts of aggregated processes to human toxicity. As noted before the acid roasting step has the most impact on this category due to the amount of hydrogen fluoride used in the step. Figure 5 shows that the acid roasting step contributes 56% of the impacts on human toxicity by itself.

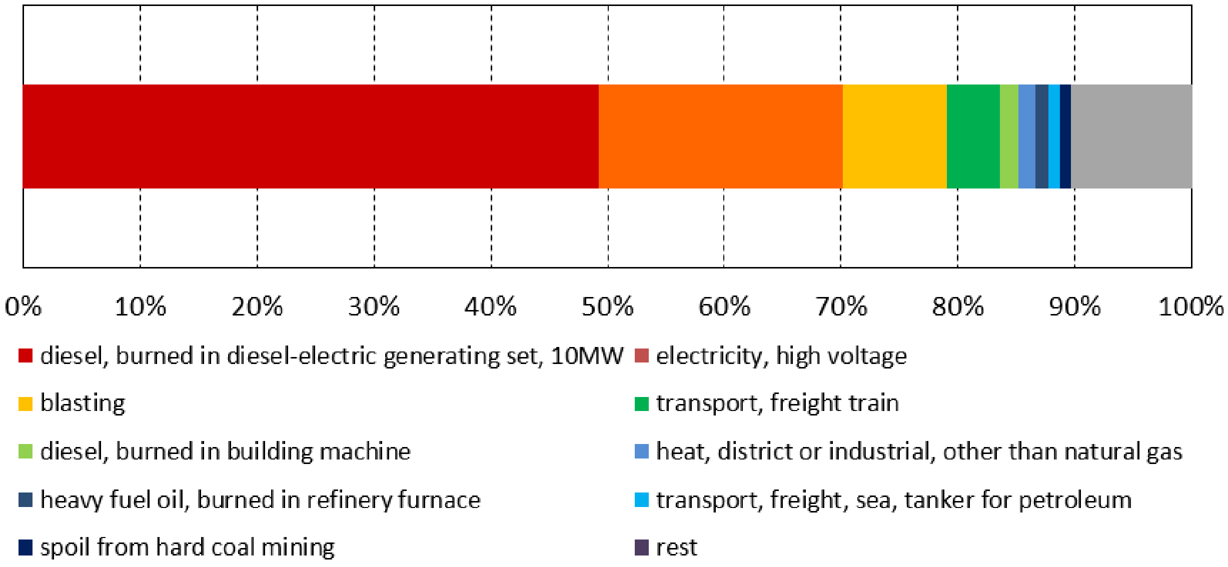

Figure 4 Process contributions to human toxicity (%)

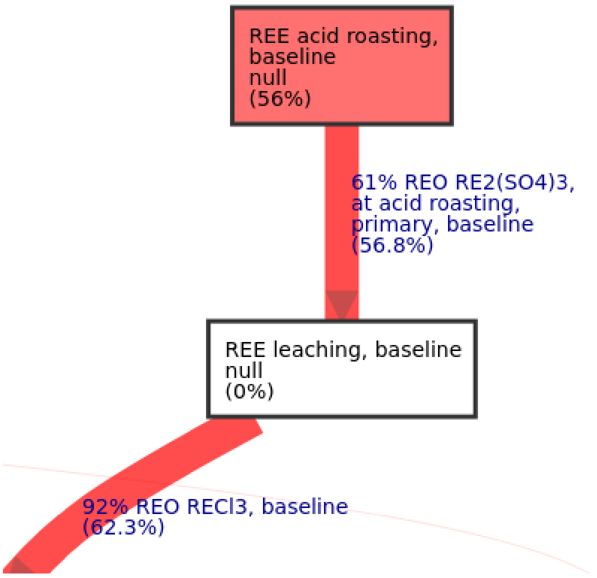

Figure 5 Process contributions REE acid roasting to human toxicity (%) in Sankey diagram

Freshwater and terrestrial acidification

Shown in Figure 6 are the reference products whose processes contribute to the total impact for freshwater and terrestrial acidification. In this impact category the most impactful processes are related to nickel mining (for electroplating) and electricity generation (for REE mining and all other steps).

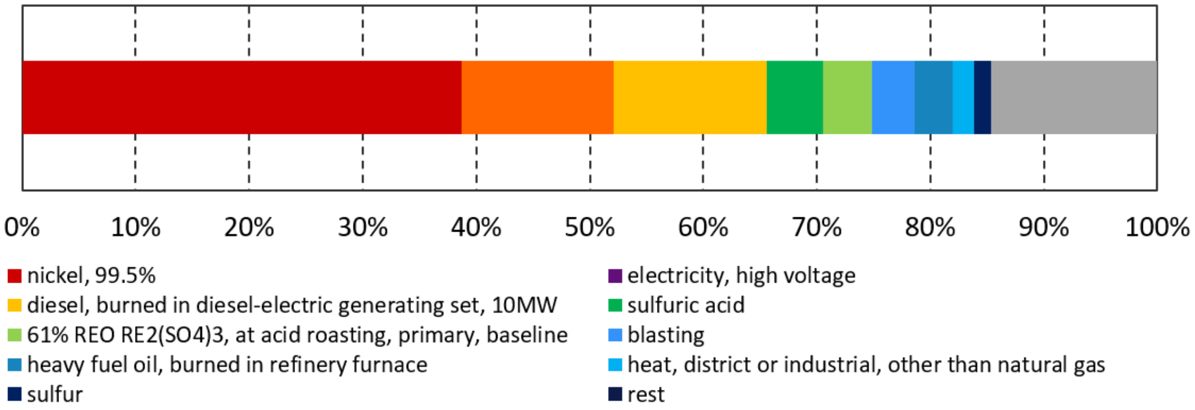

Figure 6 Process contributions to freshwater and terrestrial acidification (%)

Ozone depletion

Most impactful to the category of ozone depletion is the process of refining petroleum (used to produce diesel, generating electricity for mining). The process which produces sodium hydroxide is used in the solvent extraction step.

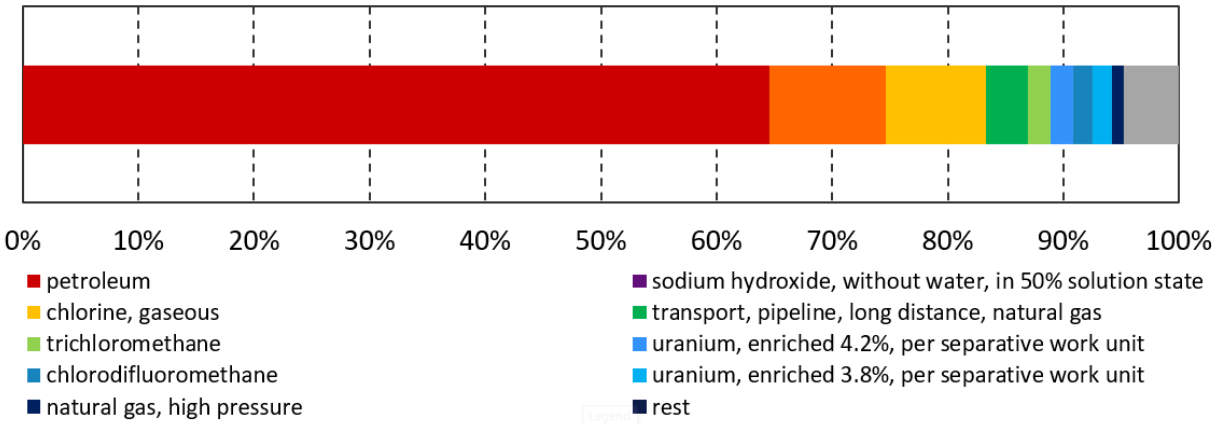

Figure 7 Process contributions to ozone depletion (%)

Ionising radiation

Contributions to this impact category come from petroleum production, which is processed into diesel and kerosene, required by the REE mining and solvent extraction steps respectively. In addition, the REE beneficiation step also contributes to this category by emission of uranium-234 and thorium-232 to air and water.

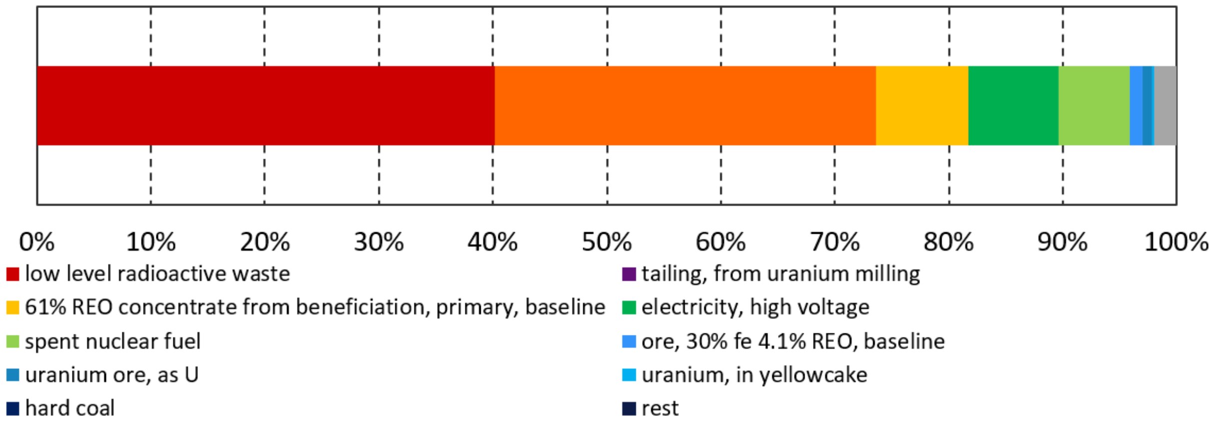

Figure 8 Process contributions to ionising radiation (%)

Metal depletion

Metal depletion impact is caused by processes that use any amount of metals, so it is no surprise that the electroplating step of the magnet production process is responsible for most of the measured impact. Both figures 9 and 10 show how the nickel used by the electroplating step contributes the majority of the impacts to metal depletion.

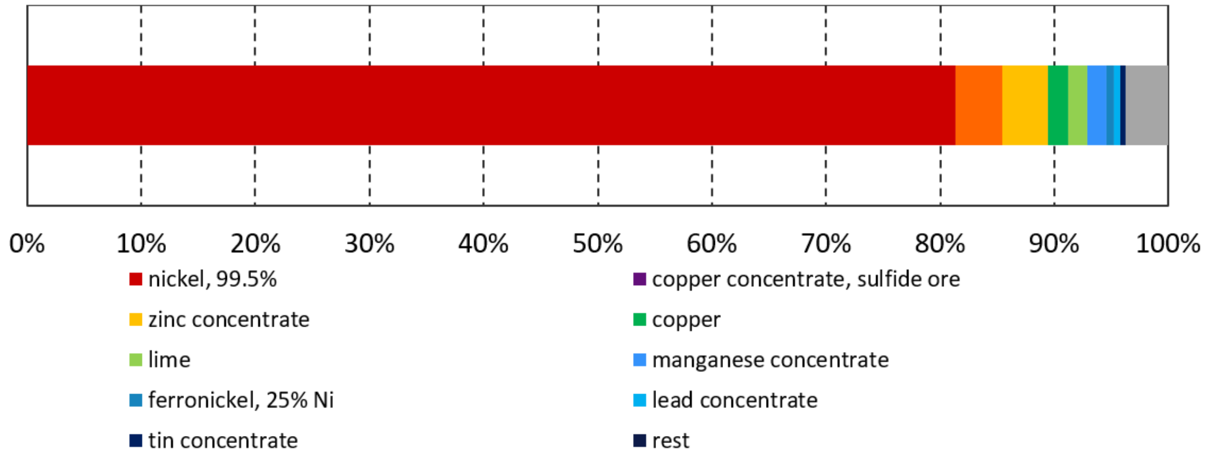

Figure 9 Process contributions to metal depletion (%)

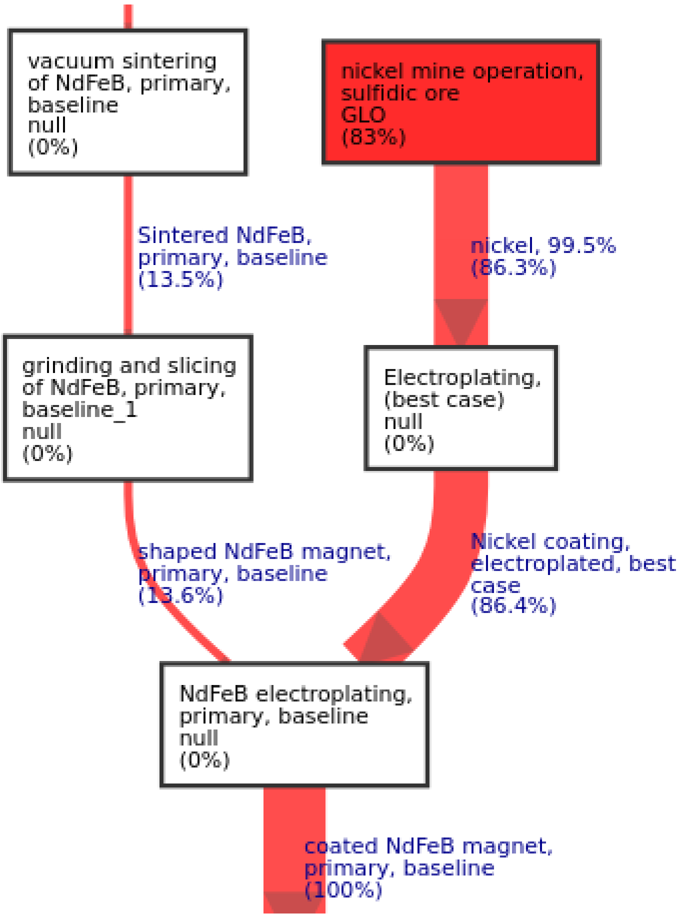

Figure 10 Process contributions NdFeB electroplating to metal depletion (%) in Sankey diagram

Freshwater aquatic ecotoxicity

Emissions that are factors of the freshwater aquatic ecotoxicity mostly occur from mining processes present in the background datasets. The most impactful of these processes are upstream of the electroplating step in the model. The Sankey diagram Figure 12 shows how the impacts from electroplating step mostly originate from the various processes handling sulfidic tailings that occur from mining nickel.

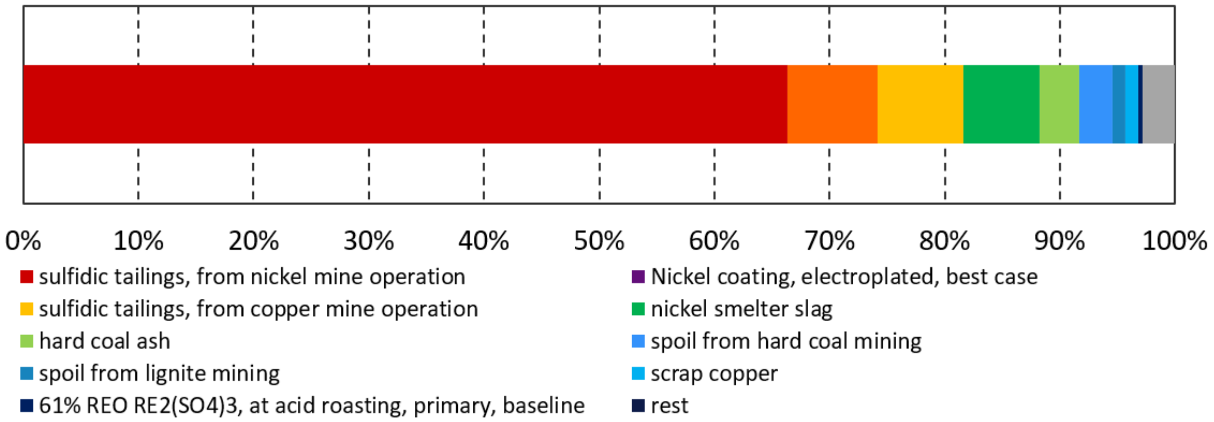

Figure 11 process contributions to freshwater aquatic ecotoxicity (%)

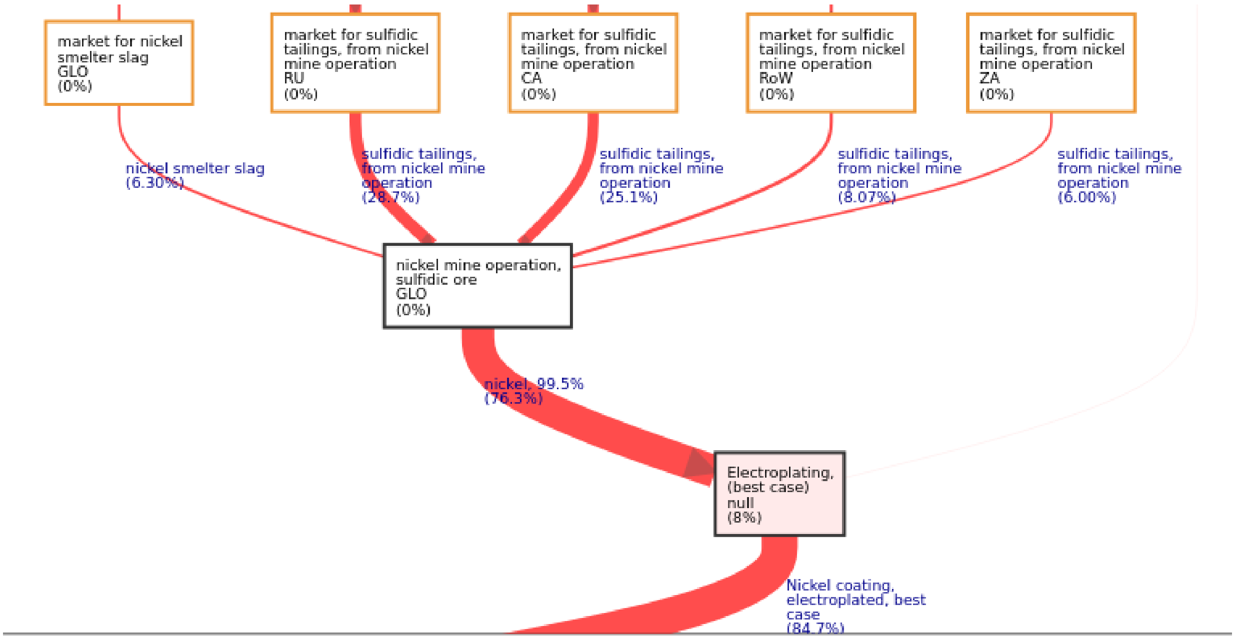

Figure 12 Process contributions electroplating to freshwater aquatic ecotoxicity (%) in Sankey diagram

Freshwater eutrophication

Freshwater eutrophication mostly includes processes that emit phosphates into the ground or water. The processes responsible for these kinds of emissions are mining processes, leading to a roughly equal split of the emissions between coal mining (for electricity generation, used by most steps in magnet production), nickel mining (electroplating step) and REE mining itself. Figure 14 shows that the Nickel coating from electroplating process contributes 39% of the total impacts on freshwater eutrophication while all of the other processes combined account for the remaining 61%.

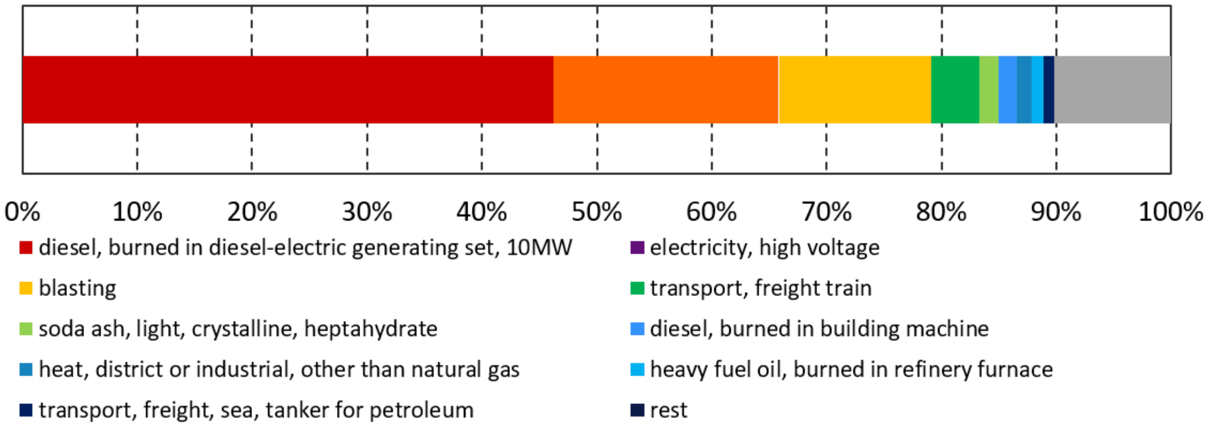

Figure 13 process contributions to freshwater eutrophication (%)

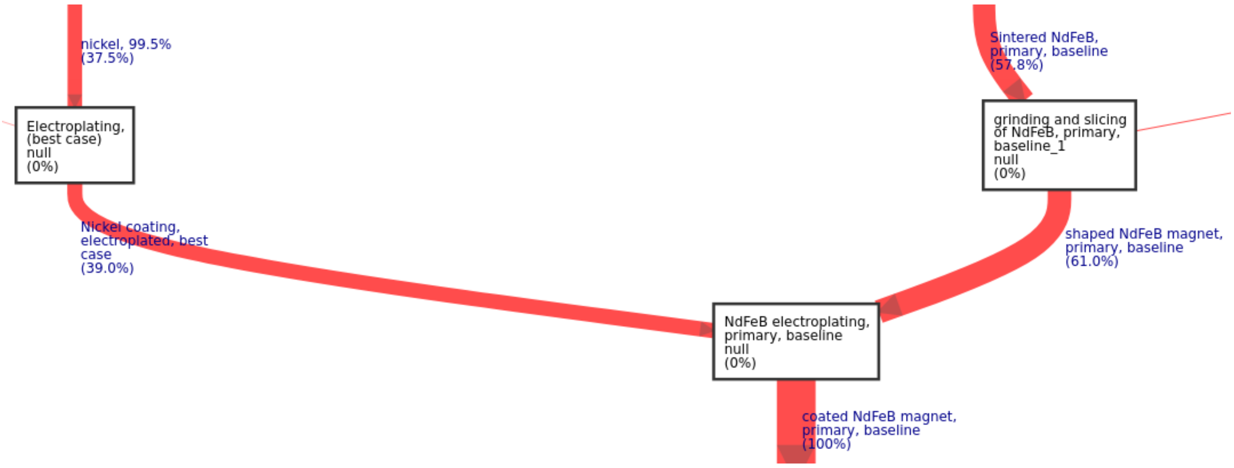

Figure 14 Process contributions electroplating to freshwater eutrophication (%) in Sankey diagram

Marine eutrophication

Marine eutrophication considers nitrogen emissions into the air or water. Half of the nitrogen emissions in this LCA can be found in REE mining step, as the model uses diesel electricity generation (a major emitter of nitrogen oxides) and blasting. The other emissions are from general electricity generation (used by all steps in the magnet production). Figure 16 shows that the electricity generated by diesel from the REE mining step accounts for 50% of the total impacts on marine eutrophication.

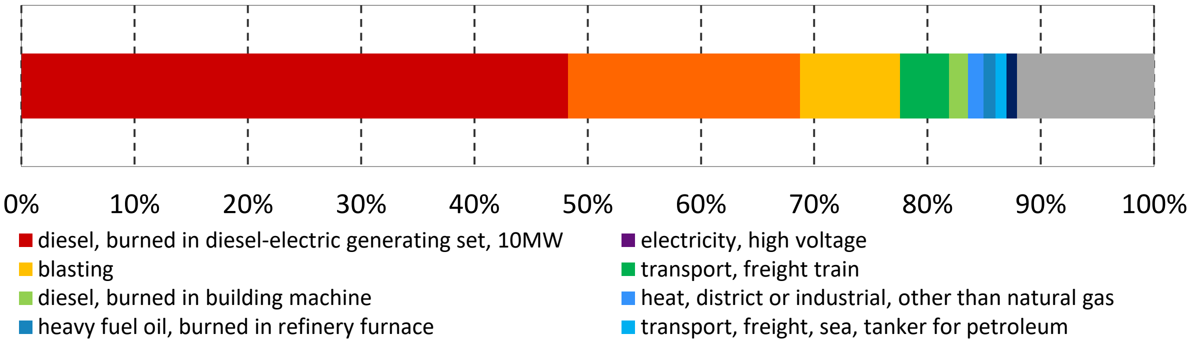

Figure 15 Process contributions to marine eutrophication (%)

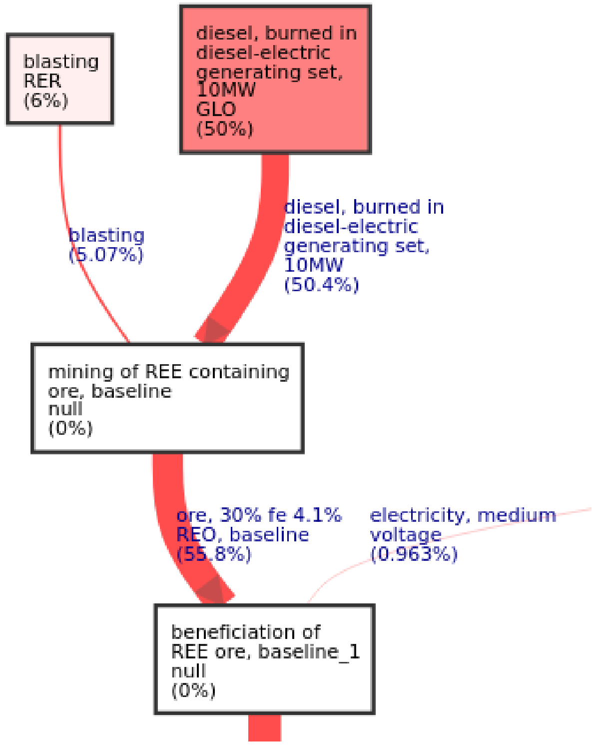

Figure 16 Process contributions REE mining to marine eutrophication (%) in Sankey diagram

4. Conclusion

The life cycle assessment of the baseline scenario of virgin Nd-Fe-B magnet production found that many of the environmental impacts originate in either the electricity generation processes used by the production line in or the mining and processing of REE ores themselves. Additionally, the use of nickel in the electroplating step is a main contributor in metal depletion and freshwater ecotoxicity and eutrophication.

Due to there being no uncertainty information in the foreground model used in the life cycle assessment, any differences in the impact found by Monte Carlo simulations can be attributed solely to the background dataset (Ecoinvent 3.6) being used by the foreground processes. While these uncertainties certainly influence the resulting impacts, they do not reveal much about the foreground processes in de virgin Nd-Fe-b magnet production.

References

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