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# APPENDIX

## Chapter 2 Supporting information

In the supplemental information we describe the collection experiment that was set up to determine the number of HDD's available in the Dutch ICT scrap. We also give a cursory analysis of the relative benefit of recycling the NdFeB magnet in the HDD, compared to the HDD itself.

### *Collection experiments*

The majority of ICT scrap in the Netherlands is collected at municipal collection stations, known as *milieustraten*. Full container loads are sold to the highest bidding WEEE processing firm. These firms must first depollute the ICT scrap. This is done via manual sorting. Batteries, monitors and printer cartridges are removed, both for legal reasons and because they can be hazardous in later processing stages. Additionally, valuable items such as cables and aluminium and printed circuit boards are separated. This depolluted ICT scrap is then shredded and sorted using gravity based sorting techniques such as water tables and wind-shifters. This results in various fractions of materials that are then sold onwards.

Because of security concerns it is customary that HDDs from companies and servers are collected separately and processed by firms specialized in the secure destruction of data. These can be collected for recycling relatively easily.

Separating HDDs out of the general ICT scrap is only feasible at the depollution stage, because of the low intrinsic value of HDD's compared to the cost of manual labour. We tried to experimentally assess what the recovery rate of this step is. These experiments were located at the Geldrop processing plant of the Dutch electronics-recycling firm Coolrec. This plant performs the depollution process of ICT recycling, where polluting (e.g. printer cartridges) or valuable components are hand-removed by teams of six to eight workers standing by a conveyor belt.

Over a four-month period, 167 containers containing in total 1343 tons of ICT scrap from four different Dutch cities were processed, with staff having received instructions to separately collect all the HDD's they could easily retrieve. Not all HDDs could easily be collected, because some were screwed tight in computer casings. In total 2566 HDDs were collected.

The researchers also participated with the experiment, analysing 27 tons of e-waste originating from three locations and noting the total number of HDD's, and whether they were recovered by factory workers or not. In our sample of three containers with 27 tons of ICT scrap the personnel collected 112 HDD's, or 4.2 HDD per ton. We were able to collect and additional 27 HDDs that could have been collected by the personnel. In the sample of 27 tons, 205 HDDs were noted as





not collectable. These figures imply that 35% to 40% of HDDs contained in personal computers can be easily separated from general ICT scrap, with the remainder destined to be shredded. This also corresponds with the experience of the plant manager, who estimates that roughly 40% of personal computers arrive with their HDDs not enclosed in the case. We speculate that this is because consumers prefer to either re-us their HDDs or remove them to assure that the data on the HDD is securely destroyed.

**Table 1** HDD collection statistics.

| | Collected | Collected by researcher | Not collected |
|---|---|---|---|
| Number | 112 | 27 | 205 |
| Kg's | 62 | 17 | |

### *Environmental benefits*

Looking at the potential benefits of recycling allows us to put the results in an environmental context. Table 2 compares the $CO_2$ emissions of producing and recycling NdFeB and aluminium. Although NdFeB has a higher emission per kg, the amount used in a typical HDD is much smaller. Therefore relative importance of recycling the aluminium content is higher. Also, these figures indicate that aluminium recycling is more efficient than NdFeB recycling, widening the gap even more.

**Table 2** CO2 emissions (avg HDD = 15 gr NdFeB and 500 gr Al).

| | Primary NdFeB | Recycled NdFeB | Primary Aluminium | Recycled Aluminium |
|---|---|---|---|---|
| Per kg | 19 | 3.25 | 12 | 1.38 |
| Per HDD | 0.29 | 0.049 | 6 | 0.69 |

Note that the $CO_2$ emission figures for NdFeB are based on Sprecher et al.,[1] while those of aluminium are based on the ecoinvent 2.3 database. Therefore they are not directly comparable and should only be taken as a rough indication to get some sense of order of magnitude.

1. Sprecher, B.; Xiao, Y.; Walton, A.; Speight, J.; Harris, R.; Kleijn, R.; Visser, G.; Kramer, G. J. Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets. *Environ. Sci. Technol.* **2014**.

# APPENDIX

## Chapter 3 - Supporting information

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### Rare earth oxide properties

Table 1 contains an overview of the rare earths taken into account in our study, with molecular weight, value and relative contribution to the rare earth content in ore.[1] This information is used extensively in the life cycle inventory, for determining conversion rates and allocation factors. Table 2 contains the composition of the REO produced in the solvent extraction process, as calculated by the authors. The calculations can be found in the supporting materials tables.

**Table 1** properties of rare earth oxid.

| Rare earth oxide | Molecular weight | Value $/kg[1] | In ore | Rare earth element | Molecular weight | In ore (g/kg ore)[2] |
|---|---|---|---|---|---|---|
| $CeO_2$ | 172.12 | 15 | 49.13% | Cerium | 140.12 | 16.4 |
| $La_2O_3$ | 325.81 | 13 | 28.15% | Lanthanum | 138.91 | 4.92 |
| $Nd_2O_3$ | 336.48 | 85 | 15.40% | Neodymium | 144.24 | 2.7 |
| $Pr_6O_{11}$ | 1021.44 | 85 | 5.07% | Praseodymium | 140.91 | 0.287 |
| $Eu_2O_3$ | 351.92 | 1820 | 0.23% | Europium | 151.96 | 0.041 |
| $Gd_2O_3$ | 362.50 | 85 | 0.58% | Gadolinium | 157.25 | 0.1 |
| $Sm_2O_3$ | 348.72 | 32 | 1.16% | Samarium | 150.36 | 0.21 |

1) Prices from www.metal-pages.com accessed 12-11-12.
2) As reported for ore from the Baotou mine.

**Table 2** composition of 1 kg REO.

| Oxide | Composition |
|---|---|
| Cerium oxide | 49.3% |
| Lanthanum oxide | 28.2% |
| Neodymium oxide | 15.5% |
| Praseodymium oxide | 5.09% |
| Europium oxide | 0.231% |
| Gadolinium oxide | 0.582% |
| Samarium oxide | 1.16% |

### Details on used method

In this section of the supporting information we give some extra details on our used method.

The process of producing neodymium oxide is already described in the ecoinvent database. However, these two background processes are very general. The ecoinvent process 'rare earth concentrate, 70% REO, from bastnäsite, at beneficiation' contains all mining and beneficiation steps while the second process 'neodymium oxide, at plant' describes the solvent extraction process. For an improved approximation of environmental impacts we split the two processes from the ecoinvent database in five processes and describe these in more detail.

For determining raw material demand in the acid roasting and solvent extraction processes we made the standard assumption to use stoichiometric balances with an assumed 95% yield.[2]

Where no literature sources on transport distances were available we assume that solvents and chemicals used in rare earth refining are produced at the coast of China. The distance from coastal China to the city of Baotou is roughly 1900 km (measured with Google maps, using the average of a route from Baotou to several large industrial areas on China's eastern coast). In the methodological overview ecoinvent assumes that for transporting chemicals in Europe on average 600 km rail and 100 km lorry transport is involved.[2] We adapted this to 1800 km rail and 100 km lorry transport.

For base chemicals we also took carrier material in account (e.g. 1 kg 30% HCl also includes 2.3 kg water), as per ecoinvent example.

For energy use we used the ecoinvent background process describing Chinese 'electricity, medium voltage, at grid'.

## Details on the life cycle inventory

**LCA modeling of ore removal from mine**

Our mining process models the production of 1 kg of ore containing 30% Fe and 4.1% REO. A recent inventory analysis of iron ore mining is given in Norgate and Haque,[3] on which we base diesel, electricity and explosives use.

We based our environmental in- and outflows on the ecoinvent background process 'iron ore, 46% Fe, at mine'. Because the mining process in Bayan Obo is equivalent to regular iron ore mining, environmental in- and outflows of our foreground process can be assumed to be the same as in the background process, after accounting for the difference in ore concentration.

The environmental inflows of rare earths are based on the mass balance. We added several environmental outflows related to radiation because of thorium containing dust that is created during mining, based on radiation emissions.[4]

*Additional assumptions*

- We neglected the overburden, topsoil and waste rock, as these are back-filled into the mine, as per ecoinvent example.

- Electricity was assumed to be generated on-site using the ecoinvent process 'diesel, burned in diesel-electric generating set'.

- Literature reports Fe contents of the Bayan Obo mine to be between 30 and 35%. We chose the lower estimate because over time the iron content of the ore will decrease.

*Scenarios*

- No differences between scenarios





**LCA modeling of beneficiation of REE containing ore**

Schuler et al.[5] estimate REO recovery rates of 40% for private and 60% for state-owned enterprises. We will assume an average 50% REO recovery rate. The ecoinvent background processes covering beneficiation of iron ore uses a 90% recovery rate of iron. We assume that the beneficiation process at Bayan Obo also attains a 90% recovery rate of iron. Using these recovery rates we calculate that the beneficiation of 30 kg of ore containing 4.1% REO and 30% Fe produces 1 kg of 61% REO concentrate[1] and 12.5 kg of 65% Fe concentrate.[2]

The milling and mechanical sorting of iron ore is described in the ecoinvent process 'iron ore, 65% Fe, at beneficiation'. Because beneficiation techniques used in the Bayan Obo mine can be assumed to be the same as in a normal iron ore mine we base the environmental in- and outflows per kg of processed ore on this process.[3] Chemicals and steam usage for the non-mechanical beneficiation processes are based on the ecoinvent reports.[1]

We also added radiation found in the tailings and dust as an environmental outflow, due to the thorium content of monazite. The tailings contain 0.028% $ThO_2$, corresponding to 1.0 kBq of radio nucleotide activity. A further 0.022 kBq is related to uranium.[4] Radiation related to dust emissions from the crushing process are estimated as follows: total dust emissions are 68 t per year.[5] Total annual production of the Bayan-obo mine in 2008 was 46.000 tons REO.[6] This means that ±1.3 kg of thorium containing dust is emitted per ton REO, equivalent to 2.1 gram per kg 61% REO ore concentrate. According to [4] this dust has a 232Th activity concentration of 1.4 Bq/g, meaning that dust related radioactivity is 0.0029 kBq.

*Allocation*

Allocation of impacts is done using economic value allocation. This allocation is rather difficult to make exactly, as the value of bastnäsite and xenotime is not available. We estimate that in 1 kg of crude ore 20% of the value is represented by iron ore while 80% is represented by the REO content.[4]

*Additional assumptions*

- Transport of ore from Bayan Obo to Baotou is modeled using ecoinvent process 'transport of coal in China using rail'. Transport of 1 kg coal by train is equivalent to 1 kg of ore. We assumed this to be equivalent, even though coal and ore differ by a factor 2 in density.[5] This assumption does not significantly impact the overall results of this LCA.

- Environmental in- and outflows for milling and sorting are comparable to regular beneficiation processes and are linearly adjusted for differences in ore concentrations.

1 1 kg * (61%/4.1%) / 50% = 30 kg
2 30 kg / (65%/30%) *90% = 12.5 kg
3 This means that we multiplied the actual figures of the ecoinvent background process by 18.1 to correct for the larger amount of ore processed per kg of economic outflow.
4 Price of 62% iron ore in September 2012 was 100$/mt, so 30% iron ore would be ± 50$/mt (www.indexmundi.com accessed 19-10-2012). Using pure REO prices (http://www.lynascorp.com/page.asp?category_id=1&page_id=25) we calculated that the REO content of 1 kg of crude ore is ± 1$/kg
5 http://simetric.co.uk/si_materials.htm accessed 20-12-2012

*Scenarios*

Recovery rates of REE have increased with improving technology. Therefore we will use the low and high estimates from literature for our low and high-tech scenarios. We assume that recovery rate of iron also increases and therefore keep the allocation factor constant.

- Baseline: 50% REE recovery rate.
- Low tech: 40% REE recovery rate.
- High tech: 60% REE recovery rate.

**LCA modelling of acid roasting**

Our process models the production of 1 kg $RE_2(SO_4)_3$. The reaction requires 1.55 kg of $H_2SO_4$ per kg of ore, of which .999 kg is consumed, 0.0465 kg is emitted as in the form of gaseous $SO_2$[6] and 0.505 kg is assumed to be disposed to landfill. We approximate this with the process 'disposal, sulphidic tailings, off-site'. 0.16 kg of heavy fuel oil is consumed for heating purposes. Additionally, 0.154 kg $CO_2$, 0.0465 kg $H_2O$ and 0.0816 kg of HF are emitted as a gas.[7]

The major reactions during acid roasting are:

$$2RECO_3F + 3H_2SO_4 = RE_2(SO_4)_3 + 2HF + 2CO_2 + 2H_2O$$

$$2REPO_4 + 3H_2SO_4 = RE_2(SO_4)_3 + 2H_3PO_4$$

In modern plants off gasses are almost completely scrubbed, leading to small emissions. However, anecdotal evidence indicates that some Chinese rare earth processing plants emit emissions directly to air. We assumed 70% scrubbing for our baseline scenario.

*Assumptions*

- The amount of $SiF_4$ is dependent on the quartz content of the ore. This is estimated to be quite low and is therefore neglected in our study.
- The reaction converts 95% of bastnäsite/monazite to rare earth sulfate.

*Scenarios*

- Baseline: 70% $H_2SO_4$ and HF gas scrubbing.
- Low tech: 30% $H_2SO_4$ and HF gas scrubbing.
- High tech: 95% $H_2SO_4$ and HF gas scrubbing.

6 $H_2SO_4$ forms 0.0465*(64/98)= 0.0305 kg $SO_2$



**LCA modelling of leaching**

For the production of 1 kg of 92% $RECl_3$, our leaching process consumes 1.77 kg of 61% rare earth concentrate from acid roasting, 1 kg of industrial grade hydrochloric acid (30%) and caustic soda. 9L of water is used per kg of ore. Water recycling rates could be very high for best practice processing plants. However, there is anecdotal evidence that more basic plants emit all of the wastewater into the environment or the large wastewater ponds surrounding Baotou. We assume a 50% recycling rate for our baseline scenario. Leaching efficiency is 96%.[7]

*Additional assumptions*

- There are significant emissions of $H_2SO_4$ and HCl into water reported in literature. However, because of the lack of impact factors available in ecoinvent, these emissions are neglected.

*Scenarios*

- Baseline: 50% wastewater recycling.
- Low tech: 0% wastewater recycling.
- High tech: 95% wastewater recycling.

**LCA modelling of solvent extraction**

Our process consumes 4.91 kg of leached 92% $RECl_3$ concentrate to produce 1 kg of 99.99% $Nd_2O_3$. As a side product we produce 3.87 kg of other rare earth oxides.

Both $RECl_3$ (253 g/mol) and P204 (322.42 g/mol) are used in a concentration of ± 1 mol/L, allowing us to calculate that we need 6.33 kg P204 / kg $Nd_2O_3$, of which 5% is consumed.[7] During the acid washing step 0.8 mol HCl (36.46 g/mol) is consumed per mol of $RECl_3$.[7] This means that we consume 0.72 kg HCl/Kg $Nd_2O_3$.[8] Furthermore, the process consumes 1.1 kg ammonium bicarbonate / Kg $Nd_2O_3$.[5] Other inputs (energy use, kerosene, capital goods) are based on the ecoinvent background process 'neodymium oxide, at plant'.

*Allocation*

We allocate environmental impacts using the economic value of the rare earth oxides, as described in the main article. The value of 1kg of neodymium oxide is \$85.00, while the combined value of the other REO's is \$78.55. For this allocation we count the praseodium content as neodymium, because in the production of NdFeB magnets it is used as such.

7 P204 is 322.43 g/mol, NdCl3 250.50 g/mol. Processing 1 kg $RECl_3$ requires 1.29 kg P204. In total we consume 1.29 * 4.91 * 0.05 = 0.317 kg P204.

8 0.03646*4 *4.91

*Assumptions*

- 95% recovery rate of rare earths
- The organic solvent is recycled with 95% efficiency
- Emissions of acids are not taken into account.
- Thorium related radiation factors are based on ecoinvent background processes.

*Scenarios*

- Baseline: 95% recovery rate, 95% organic solvent recycling.
- Low tech: 90% recovery rate, 90% organic solvent recycling.
- High tech: 99% recovery rate, 99% organic solvent recycling.

**LCA modelling of Nd-oxide reduction**

The Hall-Héroult process is modelled in the ecoinvent processes 'aluminium, primary, at plant'. This process is based on data from a modern Norwegian aluminium smelter.

The molecular properties of $Al_2O_3$ and $Nd_2O_3$ are very different (Table 1). We assumed that the inflows, outflows and emissions of aluminium production are equivalent to that of neodymium production on a per mole basis and adjusted the data accordingly.[9] The neodymium electrolysis process has a recovery rate of 97%.[7]

**Table 1** comparison of aluminium oxide and neodymium oxide.

| Property | $Al_2O_3$ | $Nd_2O_3$ |
|---|---|---|
| Molar weight g/mol | 101.961 | 336.48 |
| Density g/cm$^3$ | 4.1 | 7.24 |
| Heat capacity J/(mol*K) | 79.04 (solid) 192.5 (liquid) | 111.3 |
| Melting point C | 2040 | 2270 |
| Kg material required for 1 kg output | 1.92 | 1.20 |

*Assumptions*

- We assumed electrolysis using a fluoride system. An alternative production process is via the electrolysis of $NdCl_3$.
- All other Chinese metallurgy processes use heavy fuel oil for heating. For consistency we replaced the light fuel oil and natural gas heating system used in Norway with heavy fuel oil.

9 The ecoinvent process uses 18.83 mol $Al_2O_3$ (1.92 kg/0.102 kg/mol). Our process consumes 3.566 mol (1.20 kg/0.33648 kg/mol). Therefore we multiplied the ecoinvent environmental outflows with 0.189 (3.566 mol/18.83 mol). However, since heat capacity is not the same as molar weight flows related to heat by 0.26, based on the solid heat capacity of aluminium oxide. Electricity consumption is based on [7]. Other economic inflows (e.g. transport, disposal) are multiplied by 0.63 to account for the difference in weight.



*Scenarios*

Gorai and Jana[8] give an overview of the emissions of aluminium smelters over time, showing that emissions have reduced by a factor 50 between 1950's technology and modern plants. Although it is safe to assume that not all Nd production in China is up to modern standards, we have found no information as to what it should be. Anecdotal evidence shows that processing conditions can be very primitive.[10] Therefore we assumed a baseline emissions level of 5x best available technology (equivalent to 1995 technology, as described in Gorai and Jana[8]). Our hi-tech scenario assumes best available technology while our low-tech scenario uses 25x the emissions of hi-tech, equivalent to a 1955 technological level. This does not include process related $CO_2$ emissions, since these are stoichiometrically determined. We assume that process related CO emissions are not filtered in any scenario and therefore also remain constant.

- Baseline: 5x emissions of best available technology.
- Low tech: 25x emissions of best available technology.
- High tech: ecoinvent Hall-Héroult process (best available technology)

**LCA modelling of NdFeB alloying and strip casting**

NdFeB alloy consists of 72 mass% iron, 27 mass% neodymium and 1 mass% boron. Therefore we use as inflows 0.72 kg iron pellets, 0.013 kg boron carbide[11] and 0.27 kg Nd.
Energy use of this process is based on experiments done with an experimental set-up. NdFeB alloy is assumed to be transported from Baotou to a magnet factory. As an example we take Ningbo Konit, responsible for 40% of worldwide production of NdFeB magnets used in HDDs.[12] Distance is 2,100 km by train,[13] increased by 50% to account for packaging materials, as per example of ecoinvent background processes.[1]

*Assumptions*

- We assume no NdFeB alloy is lost during strip casting.

**LCA modelling of hydrogen decrepitation**

Decrepitation consumes 0.43wt% hydrogen and 0.1 kwh electricity.[9] We used a background process for hydrogen consumption based on the electrolysis of water.

*Assumptions*

- We assumed that the material is not de-gassed at this stage.

10 Interview with industry sources
11 1 mass% B in NdFeB, 78 mass% B in $B_4C$ = 0.0128 kg Boron Carbide input
12 Personal communication industry sources
13 maps.google.com route from Baotou to Ningbo Konit, Located at the Ningbo Economic & Technical Development Zone, Zhejiang, China.

**LCA modelling of jet milling**

Jet milling requires 1.8 kWh per kg of NdFeB. Losses during this process are negligible.[9]

**LCA modelling of aligning and pressing**

This process consumes 0.4 kWh per kg of NdFeB, and does not involve loss of material.[9]

*Assumptions*

- We assume die pressing is used, as this is the more common processing method in industry.
- The energy use for aligning is assumed to be negligible.

**LCA modelling of vacuum sintering**

Vacuum sintering 1 kg of NdFeB alloy requires 2.4 kWh of electricity.[9] We based the other emissions of our process on the ecoinvent process 'sinter, iron, at plant'.

*Assumptions*

- Sometimes hydrogen is recovered at this stage. However, this is not common and we assume that this is not the case.

**LCA modelling of grinding and slicing**

Grinding and slicing requires 1.4 kWh of electricity.[9] Losses of material are around 30-40% in China. Production in western countries is more efficient, with loss rates of 15-20%.[14] We assumed a loss rate of 30% for the baseline scenario.

*Allocation*

Because the recycled grinding losses have approximately the same value as the alloy, we use physical allocation according to the percentage recycled.

*Scenarios*

· Baseline: 30% loss rate, of which 50% is recycled.

· Low tech: 40% loss rate, none of which is recycled.

· High tech: 25% loss rate, of which 100% is recycled.

**LCA modelling of electroplating**

HDD neodymium magnets contain on average 10wt% nickel from their nickel coating. Using average nickel consumption per $m^2$ we calculate that 1 kg of magnet requires 0.068 $m^2$ of nickel coating. Moing et al.[10] give a life cycle inventory for the electroplating of 1 $m^2$ nickel coating.

14 Personal communication with industry sources.





*Assumptions*

- Our data is based on an LCA based on European technology, which might not be completely representative of Chinese electroplating facilities.
- We used sodium phosphate instead of trisodium phosphate
- We used a generic organic chemical instead of sodium glucanate
- We neglected use of sodium saccharinate (0.5 g/m2) for lack of data

*Scenarios*

Baseline and hi-tech: best-case scenario from Moing et al.[10]
Low tech: worst-case scenario from Moing et al.[10]

**LCA modelling of recycling using manual dismantling**

The environmental impact of the manual sorting and dismantling of the HDDs is assumed to be negligible. The hydrogen decrepitation is equivalent to hydrogen decrepitation of primary material. Because the recycled material has a smaller microstructure than primary material would have after decrepitation, low energy milling can be used instead of jet milling. We assume a 90% yield, to model a slight loss in functionality of the magnet compared to a primary magnet.[11]

All further processing steps are equivalent to the production process of primary NdFeB magnets, with the exception that medium voltage electricity from Great Britain is used instead of China.

*Assumptions*

- We used the best case electroplating process and improved this further by assuming that 90% of the nickel used is sourced from the ecoinvent background process ecoinvent 'nickel, secondary, from electronic and electric scrap recycling, at refinery', to model the fact that nickel can be recovered from the recycled magnet coatings.
- We assumed low energy milling to require half the energy of jet milling.

*Allocation*

The recycled electronic scrap has positive economic value, thus a part of the environmental impact of the entire production chain of the electronics in the scrap should be allocated to the output of the recycling process.[12] However, because the value of the electronic scrap can be assumed to be negligible compared to the retail value of the electronics before they became scrap, we allocate the entire environmental impact of the production chain to the use phase of the electronics.

The recycled magnet contains 10% nickel in the form of a coating. This is removed using a sieve, after hydrogen decrepitation. For our value based allocation we used a nickel price of 17$/kg[15] and 115$/kg for Nd,[16] neglecting the value of the iron and boron component in the magnet, resulting in a 5.2% allocation to nickel and 94.8% to the magnet.

15 http://www.indexmundi.com/commodities/?commodity=nickel accessed 28-01-2013
16 http://www.mineralprices.com/ accessed 28-01-2013

**LCA modelling of recycling using shredded HDDs**

Recovery rates and energy use for shredding[17] HDDs are reported in Sprecher et al.[13] We assumed that the post-leaching process is equivalent to the high-tech scenario of primary material processing, with the following changes:

- All electricity use is based on Great Britain medium voltage instead of China medium voltage.
- Transportation distances are reduced to ecoinvent standard for generic transportation within Europe.
- We assume in the leaching process that the shredder residue is pure NdFeB magnet, of which 27 wt% is Nd.
- The product of the leaching process is 1 kg of $NdCl_3$, necessitating 1.96 kg of shredder residue.[18]
- The leaching process consumes 1.2 kg $H_2SO_4$ and 0.5 kg $Cl_3$, assuming a 20% loss.[19]
- The solvent extraction process is simpler, since we only need to extract neodymium, and not the other rare earth elements. We require 1.63 kg of 92% $NdCl_3$ for the production of 1 kg of $Nd_2O_3$.[20] All other inputs are reduced by 65.4% to account for the lower amount of material that needs to be processed.

*Allocation*

- As with the manually dismantled HDDs, we allocate the environmental impact of the production of electronics to the use phase, thereby leaving it out of the scope of this LCA.
- We need to allocate the energy use of shredding the hard drive, as this results both in shredded NdFeB fragment and shredded HDD encasing, which is sold as scrap aluminium. Allocation is fairly important as the energy use for shredding accounts for a large proportion of the total energy use of this recycling route. In line with the other allocation processes we apply a value-based allocation to the energy use of shredding the HDDs. However, a value-based allocation is difficult to make because there is no market price for NdFeB from shredded HDDs. We make the following calculation:
- HDDs are worth roughly 1.33 $/kg, with an average HDD weighing 0.5 kg, valued at 66.5 $ct. We assume that one HDD yields 5 grams of NdFeB magnets. This contains 1.58 grams of Nd2O3 equivalent[21], worth 13.4 $ct. Therefore 17% of impacts are allocated to NdFeB recovery and 83% to aluminium recovery.

17 Experiments based on an RS 30 type shredder, which consumes 22 kW and shredders 6 HDDs per minute, resulting in an energy use of 0.06 kWh per HDD.
18 3.68 mol Nd * 144 gr/mol /0.27 = 1.96
19 3.68 mol Nd consumes 11 mol $H_2SO_4$ and 11 mol $HCl_3$
20 6 moles of $NdCl_3$: 1.5 kg/0.92 = 1.63 kg.
21 Mass fraction of Nd in $Nd_2O_3$ is 85.7%; 5*.27/.857= 1.58 gram



## Normalised results

Table 4 contains the normalised results of our LCA.

**Table 4** normalised results.

| Name | Primary NdFeB magnet, baseline | Recycled NdFeB magnet via hand picking | Recycled NdFeB magnet via shredding | Unit |
|---|---|---|---|---|
| eutrophication potential | 1.2E-12 | 4.8E-14 | 2.0E-13 | Year |
| acidification potential | 1.8E-12 | 1.1E-13 | 8.3E-13 | Year |
| photochemical oxidation (summer smog) | 4.7E-13 | 2.9E-14 | 2.2E-13 | Year |
| climate change | 6.3E-13 | 7.8E-14 | 2.4E-13 | Year |
| Ionizing radiation | 3.0E-13 | 1.8E-13 | 4.8E-13 | Year |
| freshwater aquatic ecotoxicity | 5.9E-12 | 2.2E-12 | 4.8E-12 | Year |
| stratospheric ozone depletion | 1.1E-14 | 4.1E-16 | 4.6E-15 | Year |
| human toxicity | 5.8E-11 | 1.4E-12 | 1.1E-11 | Year |

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