Rare Earth Elements - Purification, Separation and Recycling

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Summary

The supply issue of rare earth elements (REE) has become an increasingly important issue both economically and politically. Their industrial importance continues to increase while most production is located China, which makes the supply potentially vulnerable. As REE are vital for many important electronic products such as electric motors and hard drives, many nations have started looking for alternative supplies of these elements.

One potential source that has garnered much attention in developed regions is REE-containing waste, mainly scrapped electronics. In regions such as the EU, electronic waste could in theory cover a significant part of the demand for REE. In addition, recycling of REE should be an important part of a circular economy, especially considering the large resource demands and negative environmental impact of current REE production processes.

Though much research has been performed in the area, REE recycling is still very limited. Of the numerous methods for REE recycling from various waste fractions only a few have been tested in a larger scale. These large-scale recycling processes are either hydrometallurgical processes similar to those used in regular REE production or specific methods used to recycle pure waste fractions within a production facility.

Most recycling processes that do not use an already pure feedstock aim to produce a REE-containing concentrate that can be fed into existing, commercially available REE separation processes. The dominant separation method is multiple stage solvent extraction; the only other method in commercial use is ion exchange, which is employed where especially high purity is required.

REE recycling faces a number of challenges, such as the presence of contaminants in the feedstock, deficiencies in waste collection and processes requiring large amounts of energy and chemicals. The combination of REE recycling with recovery of other valuables from secondary raw materials is a possible synergy.
Sammanfattning

Tillgången på sällsynta jordartsmetaller (REE) är en ständigt växande fråga i dagens samhälle. De blir allt viktigare för industrin samtidigt som Kina dominerar världspröduktionen, vilket kan göra REE-försörjningen sårbar. REE är idag nödvändiga för produktionen av många viktiga elektroniska produkter, bland annat elektriska motorer och hårddiskar, och därför letar man i många länder efter alternativa källor till REE.

En möjlig källa som har blivit allt mer intressant är de avfallsfraktioner som innehåller sällsynta jordartsmetaller, i huvudsak elektroniskrot. I områden som EU skulle det elektroniskskrot som finns i teorin kunna täcka en stor del av behovet av REE. Utöver de ekonomiska och politiska aspekterna utgör återvinning av REE en viktig del av en cirkulär ekonomi, speciellt som dagens produktionsprocesser är både resurskrävande och miljöskadliga.

Även om det har forskats mycket på området är återvinningen av REE fortfarande mycket begränsad. Av de många metoder som finns har bara ett fåtal prövats i större skala, och dessa storskaliga metoder har antingen varit baserade på hydrometallurgiska processer liknande de som används i ordinarie REE-utvinningsprocesser eller på återvinning av rena avfallsfraktioner inom produktionsanläggningar.

De flesta återvinningsmetoder som inte kräver en ren avfallsfraktion som råvara har som mål att producera ett REE-innehållande koncentrat som kan matas in i existerande kommersiella REE-separationsprocesser. Den dominerande separationsmetoden är flerstegs vätskeextraktion; den enda alternativa kommersiella metoden är jonbyte, som används då man har extra höga renhetskraav.

REE-återvinningen står inför ett antal utmaningar, däribland föroreningar i de tilltänkta råvarorna, brister i avfallsinsamlingen och processer som kräver stora mängder energi och kemikalier. Synergieffekter skulle kunna uppnås genom att återvinna REE tillsammans med andra värdefulla ämnen.
1 Terminology

RE – Rare Earth/s
REE – Rare Earth Element/s
REO – Rare Earth Oxide/s. When talking about REE production numbers, this may refer to “REO equivalents by weight” as a unit of measurement rather than the chemical nature of the product.
LREE – Light Rare Earth Element/s, also known as the cerium group (Sc, La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd)
HREE – Heavy Rare Earth Element/s, also known as the yttrium group (Y, Tb, Dy, Ho, Er, Tm, Yb, and Lu)
MREE – Middle Rare Earth Elements. Occasionally some of the heavier LREE and lighter HREE are instead placed in a separate group. In this report this is only done when the MREE distinction has been used in the a cited reference.

2 Existing Plants and Methods for REE Production

REE recycling is currently very limited and often based on the methods used to produce REE from minerals. This section aims to provide an overview of the methods used to produce REE and of currently existing REE production facilities. Details of the methods currently used at specific plants are described in section 2.2.

2.1 General Methods

REE production can generally be divided into the following stages. In practice, these distinctions are blurry; for example, the separation stage also serves to remove remaining contaminants.

1. Extraction of REE-containing material such as an ore or a specific waste fraction
2. Concentration of the material (increasing the % content of REE from a very low level to about 60 – 70%)
3. Purification to produce a REE-containing mixture (usually an acidic solution) pure enough for separation
4. Separation of different REE or REE fractions present
5. Refining into a sellable product (REE compounds or metals, either pure or in defined mixtures)

2.1.1 Extraction and Concentration

REE mines usually produce a REE concentrate on-site or close to the mine. The methods used vary depending on what minerals are used, especially since most REE are byproducts from other mining operations. The following general process description was in 2011 applicable for approximately > 90 % of all ore used for extraction of REE. All described processes are very energy-intensive. (British Geological Survey, 2011)
1. Milling of ore
2. Treatment with steam and chemicals to produce a slurry (only used in some installations)
3. Separation of gangue through froth flotation. Chemicals used include fatty acids, hydroxamates and dicarboxylic acids.
4. Cleaning of the separated ore.
5. Leaching of the ore with an ammonium- or salt-based chemical solution.
6. Addition of oxalic acid to the leachate to precipitate REE oxalates.
7. Filtration.
8. Roasting of filter cake to produce REO.

Various other separations methods based on gravitation, magnetism and electrostatic forces are also used for the initial separation steps. (British Geological Survey, 2011)

One significant exception to this general description is the process for extracting REE from ion adsorption clays, for example in southern China, where direct-leaching in situ-methods are used instead. In these methods, an ammonium sulfate solution is pumped into the clay deposit to leach out the REE there. The solution is then pumped back to the surface and REE salts are precipitated from the solution by addition of ammonium carbonate. (British Geological Survey, 2011)

2.1.2 Purification and Separation

The minerals monazite and xenotime, which also both can be found in Sweden, are purified by either the acid method or the caustic soda (also called alkaline) method. (British Geological Survey, 2011)

- The acid method begins with dissolving the mineral in hot sulfuric acid followed by leaching with water to remove phosphate. The solution is then diluted to selectively precipitate thorium and REE as double sulfates.
  As this method does not give a sufficiently clean product and does not recover the phosphate content of the minerals, the caustic soda method has gradually taken its place. The acid method is to the process used for Bastnäesite at e.g. Bayan Obo (see below).

- The caustic soda method begins with dissolving the mineral in concentrated sodium hydroxide at 140 – 150 °C, which turns REE and thorium into hydroxides.
  The solution is diluted with water, precipitating REE and thorium while the phosphate remains in solution and can be recovered as trisodium phosphate, which can be sold as a byproduct. The REE in the precipitate are then selectively dissolved using concentrated hydrochloric acid. Thorium and other undissolved material are removed by filtration (British Geological Survey, 2011).
  This is the method that was used at the Rhône-Poulenc Inc. plants, which processed most of the world’s monazite in 1998. (US EPA - Office of Solid Waste, 1998)
2.1.3 Properties used for purification

Purification methods for REE are most developed in China, but French and Japanese companies also possess the technology to produce very pure products. The methods used today utilize two property differences of REE. (British Geological Survey, 2011, MEAB, 2015)

1. All REE can exist as trivalent ions, but Ce, Pr and Tb also have tetravalent ion forms and Eu, Sm and Yb have divalent ion forms. This allows for separation through selective oxidation/reduction, which is generally used to extract Ce and Eu from REE mixtures.

2. The ionic radii of lanthanides decrease with increasing atomic number (“lanthanide contraction”). This affects their basicity, which in turn influences properties such as solubility, ionic hydrolysis and complexation.
2.1.4 Methods used for purification

The selective oxidation/reduction method that has usually been used for Eu is chemical reduction by for example zinc, but more recent developed electrochemical processes are simpler, cheaper and more environmentally friendly. Electrochemical methods have also been investigated for obtaining Yb. (Yan et al., 2006)

The small chemical differences caused by the lanthanide contraction are used in four different methods, described below. Fractional crystallization and fractional precipitation are mainly historical methods; both were inefficient and labor intensive and have now been replaced by solvent extraction and ion exchange. (British Geological Survey, 2011) Ion exchange as an industrial method was gradually replaced by solvent extraction from 1960 onwards, but remains in limited industrial use in certain applications. (Enghag, 2004)

**Fractional crystallization** was the original method for separating REE, and uses the small differences in solubility for the different REE salts, mainly a large number of double salts formed from REE ions and a variety of non-REE cations and anions, with different salts used to separate different REE or groups of REE. The process involves creating a specific ionic solution using various salts, which is partly evaporated to precipitate REE salt crystals. The crystals are redissolved in a new salt mixture and the process is repeated (sometimes thousands of times) to achieve the desired separation. (Enghag, 2004)

**Fractional precipitation** is a difficult method utilizing the small difference in basicity between the separate REE. This causes REE to precipitate at different concentrations and/or pH values when a precipitant is added to a REE solution. A special variant of the method involves melting mixtures of REE nitrates, whereupon the nitrates of the least basic REE will decompose into other, less soluble, salts, allowing subsequent separation by leaching. (Enghag, 2004)

**Solvent extraction** (liquid-liquid extraction) is the most common large-scale separation method (British Geological Survey, 2011, MEAB, 2015), usually carried out as a continuous multi-stage process of repetitive fractionation in a group of mixer settlers called “batteries”. (British Geological Survey, 2011) The REE-containing aqueous feed solution is first mixed with an organic phase containing an organic solvation agent that forms complexes with REE ions. The ions are then extracted from the REE-enriched organic phase by moving it into contact with an aqueous solution where the ions have higher solubility (this step is usually called “stripping”). By adjusting the flow rates, REE can often be concentrated 10 – 100 times in such a process step, and this process is then repeated until the required purity is reached. The process can be enhanced by adding a scrubbing function, where co-extracted contaminants are removed from the organic phase. An important parameter in these processes is the pH. An interesting case is Y, which acts as a HREE in chloride media and as a LREE in thiocyanate media. (MEAB, 2015)

Due to the small differences between the different REE the process must be repeated many times to be effective, but it can be used to produce REE compounds of > 99.99 % purity. Solvent extraction works best for LREE separation and less well for HREE. (British Geological Survey, 2011) The solvent extraction is followed by precipitation of REE as carbonates, oxalates or hydroxides, filtering, washing, drying or calcining and grinding. (British Geological Survey, 2011, Enghag, 2004) A solvent extraction facility for full separation of all REE requires hundreds of process steps. (Enghag, 2004)
The organic phase in solvent extraction usually consists of active extractants with chelating properties dissolved in kerosene or aromatics. (Enghag, 2004) Organophosphorus acids such as di-2-ethylhexyl phosphoric acid (D2EHPA, DEHPA, and other abbreviations) are typical solvation agents. The distribution coefficient in such a system increases with increased REE atomic number. Other possible solvation agents include other P-containing extractants such as tri-n-octyl phosphine oxide, tributyl phosphate (TBP, which can be used to extract REE nitrates), quaternary ammonium salts (e.g. Aliquat 336) and long-chained amines such as 2-aminononadecan (N1923). (Enghag, 2004, MEAB, 2015)

Popular solvation agents for HREE have included 2-ethylhexyl hydrogen 2-ethylhexyl phosphonate (P507 or PC-88-A) and modified versions of it and bis(2,4,4-trimethylpentyl)phosphinic acid (Cyanex 272). Naphtenic acid and related carboxylic acid derivatives have also been used, though only with limited efficiency. When separating REE from ion adsorption clays in China, the two main organic extractants have been P507 and naphtenic acid, with kerosene as the solvent and iso-octane alcohol added to the naphtenic acid for Y separation. The corresponding aqueous phases use HCl, though HNO₃ is used to remove other elements than REE. (Yan et al., 2006)

In common solvent extraction processes, the acidic solvation agents are usually saponified in the organic phase by addition of a base in order to achieve the extraction, whereupon the REE are stripped from that phase by a new acidic solution in the next step. This consumes a large amounts of chemicals and creates large amounts of acidic waste. Efforts to reduce this problem include the “hyperlink process”, which is proprietary but seems to involve reuse of the organic and aqueous phases and is supposed to decrease chemical consumption and the related waste production by 30 % or more. (Yan et al., 2006)

Improvements to the solvent extraction process using phase transfer catalysis (PTC) has been investigated by Chinese researchers, and phase transfer catalysis stripping (PTCS) has been found to greatly increase stripping efficiency. One example that has been studied in detail is the D2EHPA-N235 system, with N235 (a mixture trioctyl and tridecyl amines) acting as the PTC agent by moving protons from the aqueous phase to the organic phase to replace the extracted REE ions. (Yan et al., 2006)

Ion exchange can be used to produce very pure REE. A REE-containing solution is passed over an ion exchange resin which captures the REE ions. The REE are then separated by elution using suitable eluent solutions, often containing certain complexing or chelating agents with different affinities for different REE. However, the method is described as time consuming and commercially it is only used to produce a few of the HREE on a smaller scale, for example when extreme purity (>99.999%) is required for certain electronic applications. (British Geological Survey, 2011, Enghag, 2004) Early HREE separation was done using a P507 ion exchange resin (Yan et al., 2006) and the complexing agents that have been used include EDTA. (US EPA - Office of Solid Waste, 1998)

The exact steps of a separation process will of course depend with the composition of the initial REE concentrate as well as the desired products. Typical separation flowsheets from the Chinese REE industry are shown in Figure 2 and Figure 3.
Figure 2. Typical separation flowsheet for REE from bastnäsite and monazite, from (Yan et al., 2006)

Figure 3. Typical optimized separation flowsheet for REE from ion adsorption clay deposits, from (Yan et al., 2006)
2.1.5 Refining

The REE salts produced in the separations processes are turned into metals by molten salt electrolysis and by metallothermic reduction methods. (Enghag, 2004) The processes used are technically complicated and require large amounts of electricity. (Eriksson & Olsson, 2011) Chinese companies can achieve as much as 99.9999% purity. (British Geological Survey, 2011)

For metallothermic reduction, most REE metals can be produced by the following process: The REO is treated with hydrofluoric acid to form fluoride, which is reduced with calcium, and the liquid calcium fluoride is separated from the metal. Calcium residues are then vaporized in a high temperature vacuum process, resulting in a very pure rare earth metal. However, Sm, Eu, Tm and Yb have low boiling points for this process to work, and their oxides are instead reduced in a melt with metallic La, which has a very low vapor pressure. The reduced metals are vaporized and deposit on the walls of the tantalum container where the reaction takes place. (Enghag, 2004) Barium can be used instead of calcium in the first variant, and mischmetal can be used instead of pure La in the second. (US EPA - Office of Solid Waste, 1998)

Mischmetal (a REE alloy typically composed of mostly of Ce and La with smaller amounts of Nd, Pr, other REE and iron) is produced from dried REE chlorides by batch process electrolysis using a graphite anode. (US EPA - Office of Solid Waste, 1998)

A full REE production process can be illustrated by the historical process used at the Kyrgyz Chemical-Metallurgical Plant in the Kyrgyz Republic (now the Kasha REE Plant, owned by Stans Energy Corp, which planned to reopen the plant using an improved and optimized version of the process, but were stopped due to a conflict with the Kyrgyz government) is shown in Figure 4, with a more detailed process flow sheet shown in Figure 5. (Stans Energy Corp., 2015, Stans Energy Corp., 2012)
Figure 4. Overview of the historical REE production process at the Kyrgyz Chemical-Metallurgical Plant, based on (Stans Energy Corp., 2012)
Figure 5a. Flow sheet of the historical REE production process at the Kyrgyz Chemical-Metallurgical Plant, from (Stans Energy Corp., 2011), part 1
Figure 6b. Flow sheet of the historical REE production process at the Kyrgyz Chemical-Metallurgical Plant, from (Stans Energy Corp., 2011), part 2
2.1.6 Waste Production from Concentration, Purification and Separation

REE production processes generally produce large amounts of waste. Values reported for the production of 1 tonne of REO in China are 60,000 m³ of waste gases, 200 m³ acidified water and 1.4 tonnes of radioactive waste (as most REE deposits contain uranium or thorium). The electricity needed for the energy intensive production processes comes with additional generation of waste and/or pollution (British Geological Survey, 2011), as does the production of the large amounts of chemicals required. (Schüler et al., 2011)

Possible air emissions from REE production include sulfur oxides, hydrogen chloride, hydrogen fluoride and dust, which may contain radioactive substances. Polluted water may contain radioactive substances, heavy metals, acids, fluorides and large amounts of ammonium. (Schüler et al., 2011) There are reports of emissions from REE facilities causing disease, poisoning, water pollution and destruction of farmlands. (British Geological Survey, 2011) For 1990s REE production in the US numerous types of waste produced in REE production processes were identified, including numerous types of solid waste, some of which contained lead or mercury, off-gases from several process steps (including particulates, acids, chlorine and carbon monoxide), waste solvents and processing solutions and possibly corrosive wastewater which could contain chromium, lead and ammonium. (US EPA - Office of Solid Waste, 1998)

In the separation stages, fractional crystallization and fractional precipitation generally produce waste salts and salt solutions and may produce organic waste fractions if such solvents are used. The ion exchange process produces large amounts of waste solutions, which may be acidic or basic and which contain displaced cations and complexing agents. In the solvent extraction process, all spent solids leave the process as wastes. (US EPA - Office of Solid Waste, 1998)

In more recent years the Chinese government has been working to improve the technology in and decrease the environmental problems caused by the REE industry, which has, among other things, involved closing down a large number of REE facilities. (British Geological Survey, 2011, Schüler et al., 2011)

2.2 REE Extraction and Production Plants

This list is not complete: for example, the existence of REE refining facilities in Japan are sometimes mentioned, but the names or locations of any such facilities are not readily available.
### Table 1: Overview of active REE production sites. See Table 2 for abbreviations.

<table>
<thead>
<tr>
<th>Country</th>
<th>Australia</th>
<th>China</th>
<th>China</th>
<th>China</th>
<th>Estonia</th>
<th>India</th>
<th>Kazakhstan</th>
<th>Malaysia</th>
<th>Russia</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site/s</td>
<td>Mt Weld</td>
<td>Bayan Obo</td>
<td>Sichuan</td>
<td>Ion adsorptions clay deposits</td>
<td>Silmet</td>
<td>South India &amp; Orissa</td>
<td>Stepnogorsk</td>
<td>LAMP</td>
<td>SMW</td>
<td>Mountain Pass</td>
</tr>
<tr>
<td>Extraction &amp; concentration</td>
<td>Milling, froth flotation</td>
<td>Milling, magnetic, flotation</td>
<td>Milling, gravitation, magnetic/flotation</td>
<td>ASL, ABP/OAP, HAL</td>
<td>None</td>
<td>No data</td>
<td>No data</td>
<td>None</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>Purification</td>
<td>None</td>
<td>HTSA, HAL</td>
<td>Roasting, HAL, HP, HAL</td>
<td>As above</td>
<td>No data</td>
<td>CSM</td>
<td>No data</td>
<td>HTSA</td>
<td>HTCR, SASL, CP</td>
<td>Acid leaching</td>
</tr>
<tr>
<td>Separation</td>
<td>None</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>No data</td>
<td>SE, FP</td>
<td>No data</td>
<td>SE</td>
<td>No data</td>
<td>SE</td>
</tr>
<tr>
<td>Refining</td>
<td>None</td>
<td>LREE: MSE, HREE: VMR</td>
<td>No data</td>
<td>No data</td>
<td>No data</td>
<td>No data</td>
<td>No data</td>
<td>CP/HP/OAP, CA</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>State</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
<td>Active/Startup</td>
<td>Active</td>
<td>Suspended</td>
<td></td>
</tr>
</tbody>
</table>
A: Performed at the LAMP site in Malaysia.

B: Double sulfate precipitation and ammonium carbonate extraction might also be involved. About 10% might instead be treated by an alkali-based method.

C: Including pure metals, salts and alloys

D: Actual products, the ore extraction is far larger

E: Concentrate is supplied by the Mt Weld site in Australia.

F: Capacity of at least 8,000 tonnes REO and 5,000 tonnes LREE concentrate

Table 2: Guide to the abbreviations used in Table 1.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABP</td>
<td>Ammonium bicarbonate precipitation</td>
</tr>
<tr>
<td>FP</td>
<td>Fractional precipitation</td>
</tr>
<tr>
<td>MSE</td>
<td>Molten salt electrolysis</td>
</tr>
<tr>
<td>ASL</td>
<td>Ammonium sulfate leaching</td>
</tr>
<tr>
<td>HAL</td>
<td>Hydrochloric acid leaching</td>
</tr>
<tr>
<td>OAP</td>
<td>Oxalic acid precipitation</td>
</tr>
<tr>
<td>CA</td>
<td>Calcination</td>
</tr>
<tr>
<td>HP</td>
<td>Hydroxide precipitation</td>
</tr>
<tr>
<td>SASL</td>
<td>Sulfuric acid and ammonium sulfate leaching</td>
</tr>
<tr>
<td>CP</td>
<td>Carbonate precipitation</td>
</tr>
<tr>
<td>HTCR</td>
<td>High temperature chlorine gas reduction</td>
</tr>
<tr>
<td>SE</td>
<td>Solvent extraction</td>
</tr>
<tr>
<td>CSM</td>
<td>Caustic soda method</td>
</tr>
<tr>
<td>HTSA</td>
<td>High temperature treatment with sulfuric acid</td>
</tr>
<tr>
<td>VMR</td>
<td>Vacuum metallothermic reduction</td>
</tr>
</tbody>
</table>

2.2.1 China

In 2010 China was responsible for 97% of REO mining, concentration and separation as well as almost all refining of REO into REE metal. In 2011 there were about 100 companies working with separation, smelting and refining of REE in China; however, the industry is currently going through a large consolidation on the government’s initiative, where production is being regulated and companies (especially small and/or illegal operations) are forcibly merged or closed in an effort to produce an industry with fewer and larger companies. The initiative also involves improving the technology used and reducing the environmental impact through much stricter regulations and various other project that were planned to be completed in 2015. (Schüler et al., 2011)

Bayan Obo, Inner Mongolia

The main part of Chinese REE production comes from the Bayan Obo mine, which is the world’s largest REE-producing mine. The main product of the mine is iron ore; REE are extracted as a byproduct. In addition to mining, the site also contains facilities for REE concentration and refining. (British Geological Survey, 2011)

The ore from the mine is milled and then concentrated through magnetic separation and flotation. (Schüler et al., 2011) Two different sources have somewhat different descriptions of the purification process, shown in Table 1.
Table 3: Descriptions of the Bayan Obo REE concentration & purification process.

<table>
<thead>
<tr>
<th>(Schüler et al., 2011)</th>
<th>(British Geological Survey, 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-temperature roasting in concentrated sulfuric acid to remove fluoride and carbon dioxide</td>
<td>Treatment with sulfuric acid at 300 – 600 °C</td>
</tr>
<tr>
<td>Leaching with water followed by filtration to remove impurities</td>
<td>Leaching with water followed by filtration to remove impurities</td>
</tr>
<tr>
<td>Leaching with extractant solutions containing ammonium bicarbonate and hydrochloric acid to produce REE chlorides</td>
<td>Precipitation of REE as double sulfates</td>
</tr>
<tr>
<td></td>
<td>Conversion of REE double sulfates into hydroxides</td>
</tr>
<tr>
<td></td>
<td>Purification by leaching with hydrochloric acid</td>
</tr>
</tbody>
</table>

According to (Schüler et al., 2011) 90 % of extracted REE ore is purified through the process described in Table 3 and the remaining 10 % are treated using an alkali-based method (probably the “caustic soda method” described previously).

After purification, the REE are separated by solvent extraction, mainly based on P507 (C₁₆H₃₅O₃P) and hydrochloric acid. They are then precipitated using ammonium bicarbonate or oxalic acid, and the precipitate is thermally oxidized into REO. LREE are then produced by chloride- or oxide-based molten salt electrolysis and HREE by vacuum metallothermic reduction at 1450 – 1750 °C. (Schüler et al., 2011)

The mine produces thorium-rich waste that pollutes the surroundings (including the groundwater) through water and airborne dust. The refining process releases large quantities of gas (containing fluoride, sulfur oxides and dust), polluted and acidified water and radioactive waste material. (Schüler et al., 2011)

**Sichuan**

In the Sichuan mine the ore is first milled and then separated first by gravitation and then by magnetic separation or flotation, reaching an REO concentration of 70 %. The REE concentrate is roasted at 600 °C to remove carbon dioxide and then leached with hydrochloric acid. REE are precipitated by adding sodium hydroxide and the precipitate is leached again to produce REE chlorides. This is followed by a separation using the same process as in Bayan Obo. (Schüler et al., 2011)

The solid waste and wastewater produced contain fluorine and thorium. (Schüler et al., 2011)

**Southern China**

REE are extracted from the ion adsorption clay deposits in Southern Chine by the process called in situ leaching. They clays are leached using ammonium sulfate, directly producing a REE concentrate through ion exchange. After recovering the concentrate, the REE are precipitated using ammonium bicarbonate or oxalic acid, giving a 92 % REO precipitate that is leached with hydrochloric acid and fed to the same separation process as in Bayan Obo and Sichuan. (Schüler et al., 2011)
2.2.2 Australia

In proximity to their Australian Mt Weld mine, Lynas Corporation runs a REE concentration facility, where the ore from the mine is milled and concentrated by froth flotation. The concentrate is then transported to a facility in Malaysia for further treatment (see below). (Lynas Corporation, 2012)

2.2.3 Estonia

Molycorp Silmet (previously Silmet Rare Metals) is a company of Soviet origin that was bought by Molycorp (owners of the Mountain Pass REE mine in California see below). In 2015 they claimed to produce 700 tonnes of REE metal products and 3,000 tons other REE products, including pure metal, various metal salts and alloys (among these NdFeB and mischmetal). The process waste contains ammonium and fluoride, which is converted into liquid nitrogen fertilizer and ammonium bifluoride byproducts. (Molycorp, 2015a)

Molycorp’s operations outside of North America were excluded from the company’s 2015 filing for bankruptcy, and as of August 26, 2015 the facility in Estonia was continuing its production. (Molycorp, 2015b, Molycorp, 2015c)

2.2.4 India

Indian Rare Earths Ltd (IRE) produces REE compounds as a byproduct of uranium and thorium extraction using the caustic soda method. In 2010 their facilities produced less than 50 tonnes REO of actual product, though the amount of extracted ore was far larger. (British Geological Survey, 2011) IRE have four production facilities, mainly in southern India and Orissa, and parts of the REE are refined locally to produce up to 99.9 % REO and other REE compounds. The processes used are multi-stage solvent extraction and fractional precipitation, and high purity oxides are produced by “RED”. (Indian Rare Earths Ltd, 2015)

2.2.5 Kazakhstan

In 2010, the joint venture Summit Atom Rare Earth Company LLP (Sareco) was established by the Japanese company Sumitomo Corporation and the state-owned Kazakhstani nuclear company Kazatomprom. They plan to extract REE from uranium mine tailings in Kazakhstan, aiming at 15,000 tonnes of REO by 2015. (British Geological Survey, 2011) Their first factory was opened in Stepnogorsk November 2012, aiming for an initial production of 1,500 tons of mixed rare earth carbonate per year. They were also working on developing separation processes for high-purity products in cooperation with Shin Etsu Chemical Co. (Sumitomo Corporation, 2012)

2.2.6 Malaysia

Since a few years back, Lynas Corporation runs the Lynas Advanced Materials Plant (LAMP) at Gebeng Industrial Estate in Pahang, Malaysia. They are supplied with a REE-concentrate mostly consisting of REE-containing phosphate mineral from the company’s Mt Weld mined in Australia (see above). At LAMP, the concentrate is mixed with concentrated sulfuric acid and cracked at high temperature in a rotary kiln to produce REE sulfates. Leaching with water removes impurities such
as iron phosphogypsum and the solution is then neutralized. This is followed by separation through the following solvent extraction steps:

Upstream 1: Extraction of Sm, Eu, Gd and heavier REE.

Upstream 2: Extraction of Ln, Ce, Pr and Nd

Upstream 3: Removal of iron from the solution with heavier REE

Downstream 1: Didymium (Pr and Nd) extracted from the Ln-Ce-Pr-Nd solution

Downstream 2: Ce extracted from the Ln-Ce solution

Downstream 3: Sm removed from the didymium solution

Lastly, the REE are precipitated as carbonates, hydroxides or oxalates. Some of them are then calcined to produce REO. (Lynas Corporation, 2013)

Waste production: Sulfur oxides from cracking and leaching are treated to form a gypsum product. Iron phosphogypsum from leaching and acidified water are neutralized to form a magnesium-rich gypsum product. The company aims to sell these as byproducts. (Lynas Corporation, 2013)

In June 2014, the company had reached a production rate of roughly 7,500 tonnes of REO equivalents per year, but the facility was still under construction and the process hadn’t been optimized. They were working on registering their byproducts and commercializing them. (Lynas Corporation, 2015)

### 2.2.7 Russia

Some REE ore is produced from mining on the Kola Peninsula, and this is refined by Solikamsk Magnesium Works (SMW) to produce REE chlorides and carbonates. The REE ores are treated with chlorine gas at high temperature in the presence of reductants to produce REE chlorides. Other metals are separated from the cake produced, which is then dissolved in sulfuric acid and ammonium sulfate. The solution is then diluted with water and sodium carbonate to precipitate REE and thorium. (British Geological Survey, 2011)

### 2.2.8 USA

For a long time the Mountain Pass mine in California dominated the world’s REE production before being closed due to growing competition from China and environmental problems. The mine was restarted by the owners, Molycorp, in the early 2010’s and in October 2013 it produced ca 8,000 tonnes of REO equivalents as well as 5,000 tonnes of LREE concentrate. They were then planning to increase the production to 15,000 tonnes of REO equivalents in the near future. (Molycorp, 2013a)
Molycorp filed for bankruptcy on June 25, 2015. (Molycorp, 2015c) A key factor was the dramatic price decrease for REE in the preceding years. On August 26 the same year they announced that the production at the Mountain Pass facility would be suspended and moved to “care and maintenance” mode no later than October 20, 2015. (Molycorp, 2015b)

The restarted facility dissolved the REE-containing minerals in acid and extracted HREE through counter-current solvent extraction. (Molycorp, 2013b) The previous process used flotation to produce a bastnäsite concentrate, which was calcined to drive of carbon dioxide and fluorine and leached with HCl to produce an REE solution for separation and refining. (US EPA - Office of Solid Waste, 1998)

### 3 Recycling of REE: The Current Situation

The recycling of REE is currently very limited; less than 1% of all REE are recycled (Tsamis and Coyne, 2015, British Geological Survey, 2011) and recycling is mostly limited to permanent magnets and polishing compounds (Tsamis and Coyne, 2015) as well as smaller amounts from batteries and lamps (Gambogi, 2015). Much research and development work has been done, but very little of it has moved beyond lab-scale tests. (Tsamis and Coyne, 2015)

#### 3.1 REE Distribution in the Technosphere

Figure 6 gives an overview of global applications for different REE. Table 1 shows the % distribution of REE usage for different applications and Table 2 shows a projection of the amounts of REE available for recycling available in some interesting waste fractions.
Figure 7. Global applications of REE. From (Schüler et al., 2011)

Table 4. REE usage by application, in %. From (Binnemans et al., 2013)

<table>
<thead>
<tr>
<th>Application</th>
<th>La</th>
<th>Ce</th>
<th>Pr</th>
<th>Nd</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd</th>
<th>Tb</th>
<th>Dy</th>
<th>Y</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Battery alloys</td>
<td>50</td>
<td>33.4</td>
<td>3.3</td>
<td>10</td>
<td>3.3</td>
<td>2</td>
<td>0.2</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallurgy</td>
<td>26</td>
<td>52</td>
<td>5.5</td>
<td>16.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auto catalysts</td>
<td>5</td>
<td>90</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC</td>
<td>90</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polishing powders</td>
<td>31.5</td>
<td>65</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass additives</td>
<td>24</td>
<td>66</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphors</td>
<td>8.5</td>
<td>11</td>
<td></td>
<td></td>
<td>4.9</td>
<td>1.8</td>
<td>4.6</td>
<td>69.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>17</td>
<td>12</td>
<td>6</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>53</td>
</tr>
<tr>
<td>Others</td>
<td>19</td>
<td>39</td>
<td>4</td>
<td>15</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a The percentages are estimated average consumption distribution by application; the actual distribution varies from manufacturer to manufacturer.*
Table 5. Global recycling potential for REE from magnets, NiMH batteries and lamp phosphors (Binnemans et al., 2013)

<table>
<thead>
<tr>
<th>Application</th>
<th>Estimated REE stocks in 2020 (tons)</th>
<th>Estimated average lifetime (years)</th>
<th>Estimated REE old scrap in 2020 (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td>300,000</td>
<td>15</td>
<td>20,000</td>
</tr>
<tr>
<td>Phosphors</td>
<td>25,000</td>
<td>6</td>
<td>4167</td>
</tr>
<tr>
<td>NiMH batteries</td>
<td>50,000</td>
<td>10</td>
<td>5000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>375,000</strong></td>
<td><strong>-</strong></td>
<td><strong>29,167</strong></td>
</tr>
</tbody>
</table>

3.2 Permanent Magnets

The permanent magnets used in modern technology (such as hard drives) usually consist of a neodymium-rich NdFeB alloy, that might also contain smaller and varying amounts of Pr, Gd, Tb, Dy and other metals. < 2 % of permanent magnets instead consist of a SmCo alloy free from other REE than Sm. About 30 % of the magnetic alloy becomes process waste during production, but this waste is usually recycled by the companies themselves, who don’t reveal much about the recycling methods used. (Binnemans et al., 2013)

Products containing permanent magnets become electronic waste, which is shredded and melted down for recycling of other metals. During this process the REE that are present in the waste are oxidized and become part of the smelter slag. (Binnemans et al., 2013)

Hitachi Ltd recovers permanents magnets from hard drives and compressors that the company produces. The products are separated into their constituent parts, after which the magnets can be separated by hand. (Binnemans 2013)

Reuse of permanent magnets used for medical MRI has been reported. (Schüler et al., 2011)

3.3 Batteries

NiMH-batters contain 8 – 10 % REE, namely La, Ce, Pr and Nd, which are generally lost in the smelter slag when the batteries are melted down to recover Ni. (Binnemans et al., 2013)

Umicore N.V. and Rhodia (now owned by the Solvay group) have developed a method based on Umicore’s patented UHT smelting technology to recover material from NiMH and lithium-ion batteries. An industrial pilot plant started in Hoboken, Belgium, in September 2011 is supposed to be able to handle 7,000 tonnes of batteries per year. The batteries are fed into an oven with coke and slag formers (the main part of the energy need is supplied by plastic materials and organic electrolytes from the batteries themselves) and REE end up in the slag, which can then be treated to produce a REE concentrate which is sent to Rhodia’s REE separation facility in La Rochelle, France, to produce REO. (Binnemans et al., 2013, Umicore N.V., 2015)
In March 2013 Honda Motor Co started recovering REE from NiMH batteries in a facility belonging to Japan Metals & Chemicals Co. The batteries are collected, dismantled, calcined and pulverized. The powder is separated into different fractions and fractions containing REE are dissolved in acid to produce REO. These are treated by molten salt electrolysis to produce REE in metal form. (Honda Motor Co. Ltd., 2013)

### 3.4 Lamp Phosphors

Depending on the type of lamp, phosphors may contain up to 27.9 weight% of La, Ce, Eu, Gd, Tb and/or Y. Though lamps are currently collected for recycling of glass, metal and plastic, the phosphors are generally landfilled. The mixed fraction containing lamp phosphors is problematic since it contains many different substances, some of which will cause problems with existing recycling methods (for example mercury from certain types of lamps and sulfides from cathode ray tubes). Due to variations in composition, direct reuse of phosphors in new lamps is only possible if it is the same type of lamp from the same producer, and even then aging phenomena will have affected the quality of the phosphor. (Binnemans et al., 2013)

Possible methods to separate different phosphors a mixed fractions include (Binnemans et al., 2013):

- **Froth flotation:** More difficult than in the mining industry due to smaller particles and the presence of different substances with similar hydrophobicity. Can be used to separate phosphors from accompanying halophosphate.
- **Two phase (polar and non-polar) flotation:** Can achieve purities of > 90 % when separating different phosphors.
- **Pneumatic separation:** Limited due to variations in particle sizes.
- **Density-based separation:** As halophosphate has a lower density than phosphors it can be separated using diiodomethane, which has a density between that of phosphors and halophosphate.

In 2012 Rhodia (by then a part of Solvay group) started processes to recycle REE from old lamp phosphors in France. (Tsamis and Coyne, 2015) The phosphors are sent to a facility in Saint Fons, where the powders are suspended in a water solution and chemically treated, then separated and dried. Waste water and waste gases are produced and treated. (Solvay S.A., 2014)

The REE concentrate is then sent to their La Rochelle facility. There, it first goes through a pyrometallurgical thermal treatment followed by resuspension, filtration and washing. Nitric acid is added to dissolve all material and REE are separated through solvent extraction. The separated REE are then precipitated, filtrated and calcined and the recovered REE are used to produce new phosphors. Waste gas and effluents are produced and have to be treated. (Solvay S.A., 2014, Rhodia (Solvay group))

### 3.5 Miscellaneous

Small amounts of yttrium are recycled, mainly from laser crystals and synthetic garnets. (Schüler et al., 2011)
4 Recycling of REE: Other Possible Methods

4.1 Permanent Magnets

Table 6. Overview of different recycling methods for REE magnets, taken from (Binnemans et al., 2013)

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct re-use in current form/shape</td>
<td>Most economical way of recycling (low energy input, no consumption of chemicals)</td>
<td>Only for large easily accessible magnets (wind turbines, large electric motors and generators in hybrid and electric vehicles)</td>
</tr>
<tr>
<td></td>
<td>No waste generated</td>
<td>Not available in large quantities in scrap today</td>
</tr>
<tr>
<td>Reprocessing of alloys to magnets after hydrogen decrpetition</td>
<td>Less energy input required than for hydrometallurgical and pyrometallurgical routes</td>
<td>Not applicable to mixed scrap feed, which contains magnets with large compositional variations</td>
</tr>
<tr>
<td></td>
<td>No waste generated</td>
<td>Not applicable to oxidized magnets</td>
</tr>
<tr>
<td></td>
<td>Especially suited for hard disk drives (little compositional change over the years)</td>
<td></td>
</tr>
<tr>
<td>Hydrometallurgical methods</td>
<td>Generally applicable to all types of magnet compositions</td>
<td>Many process steps required before obtaining new magnets</td>
</tr>
<tr>
<td></td>
<td>Applicable to non-oxidized and oxidized alloys</td>
<td>Consumption of large amounts of chemicals</td>
</tr>
<tr>
<td></td>
<td>Same processing steps as those for extraction of rare earths from primary ores</td>
<td>Generation of large amounts of waste water</td>
</tr>
<tr>
<td>Pyrometallurgical methods</td>
<td>Generally applicable to all types of magnet compositions</td>
<td>Larger energy input required</td>
</tr>
<tr>
<td></td>
<td>No generation of waste water</td>
<td>Direct smelting and liquid metal extraction cannot be applied to oxidized magnets</td>
</tr>
<tr>
<td></td>
<td>Fewer processing steps than hydrometallurgical methods</td>
<td>Electroslag refining and the glass slag method generate large amounts of solid waste</td>
</tr>
<tr>
<td></td>
<td>Direct melting allows obtaining master alloys</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liquid metal extraction allows obtaining REEs in metallic state</td>
<td></td>
</tr>
<tr>
<td>Gas-phase extraction</td>
<td>Generally applicable to all types of magnet compositions</td>
<td>Consumption of large amounts of chlorine gas</td>
</tr>
<tr>
<td></td>
<td>Applicable to non-oxidized and oxidized alloys</td>
<td>Aluminum chloride is very corrosive</td>
</tr>
<tr>
<td></td>
<td>No generation of waste water</td>
<td></td>
</tr>
</tbody>
</table>
Traditional recovery methods for REE are based on hydrometallurgical techniques and have mostly been aimed towards pure magnets and scrap alloy from production facilities. The alloys are dissolved in strong mineral acids and selectively precipitated as double sulfates, oxalates or fluorides. Elements such as boron, copper and nickel must then be removed before the solution can be fed to a conventional REE separation process. Older methods were generally developed for the recycling of SmCo-magnets, which were commercially viable to recycle in the 1990s are easier to process since the only contain one REE and lack surface plating. (Binnemans et al., 2013) The hydro- and pyrometallurgical methods are generally based on mature technology, but the REE applications have rarely been tested outside of laboratories. (Tsamis and Coyne, 2015)

Rhône-Poulenc (later Rhodia, now acquired by the Solvay group) developed the following method for recycling SmCo-alloys (SmCo₅ and Smₓ(Co, Fe, Cu, Zr)₁₋ₓ). (Binnemans et al., 2013)

1. The alloy is dissolved in sulfuric, nitric, hydrochloric or perchloric acid (which acid is used depends on the later parts of the process; nitric and hydrochloric acid are preferable when using solvent extraction, while sulfuric acid can be used when selective precipitation follows). Sm, Co, Fe and Cu are dissolved, while Zr is not and can be removed by filtration.
2. Sm is extracted by selective precipitation or solvent extraction.
   a. Selective precipitation: Sm is precipitated as oxalate by addition of oxalic acid (samarium oxalate has a very low solubility in strong, non-oxidizing acids) or as a double sulfate together with Na by addition of sodium sulfate. The transition metals remain in solution.
   b. Solvent extraction: Samarium can be selectively extracted using tri-n-butyl phosphate (TBP) or Di-(2-ethylhexyl)phosphoric acid (D2EHPA).

A method developed at the University of Birmingham for recycling sintered REE-magnets from computer hard drives has been tested on a smaller scale. The hard drives are opened mechanically and the magnetic alloy is hydrogenated by hydrogen gas at atmospheric pressure. This causes the alloy to expand and break apart into granules or powder. After further treatment to reduce the Ni content, the granules or powder can be used to produce new magnets of lower quality or as a feedstock for REE recovery. (Binnemans et al., 2013)
4.2 Batteries

Table 7. Overview of different recycling methods for REE from batteries, taken from (Binnemans et al., 2013)

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Hydrometallurgical routes   | • Low investment costs  
  • Recycling possible of different waste fractions (cathode and anode materials, metals from casing) that can be marketed separately | • Many manual operations are required for dismantling of batteries and separating the different components  
  • Large consumption of chemicals |
| Pyrometallurgical routes    | • Well-developed technology  
  • Energy recovery from plastic casings and other organic components  
  • Same processing steps used for extracting REEs from slags as from primary ores | • High investment cost for furnace  
  • REEs need to be extracted from slags  
  • REEs are obtained as mixtures and further separation is required |

For NiMH batteries numerous hydrometallurgical methods similar to those intended for permanent magnets have been suggested. (Binnemans et al., 2013) By performing the process in a non-oxidizing environment Ni dissolution can be avoided, which reduces the consumption of chemicals and makes subsequent steps easier. (Larsson, 2012)
4.3 Lamp Phosphors

Table 8. Overview of different recycling methods for REE-containing lamp phosphors, taken from (Binnemans et al., 2013)

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct re-use</td>
<td>• Very simple method</td>
<td>• Only applicable to one type of fluorescent lamps, because different lamps make use of different phosphor mixtures</td>
</tr>
<tr>
<td></td>
<td>• No chemical processing required</td>
<td>• Phosphors deteriorate over the lifetime of the lamp</td>
</tr>
<tr>
<td>Separation of phosphors in individual components</td>
<td>• Relatively simple process</td>
<td>• Very difficult to obtain very pure phosphor fractions</td>
</tr>
<tr>
<td></td>
<td>• No or limited amounts of chemicals are consumed</td>
<td>• Separation process may change the phosphor particle size</td>
</tr>
<tr>
<td>Recovery of REE content</td>
<td>• Generally applicable to all types of phosphor mixtures</td>
<td>• Phosphors deteriorate over the lifetime of the lamp</td>
</tr>
<tr>
<td></td>
<td>• Same processing steps as those for extraction of rare earths from primary ores</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Gives very pure rare-earth oxides that can also be used for other applications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Many process steps required before obtaining new lamp phosphors</td>
<td>• Consumption of large amounts of chemicals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Generation of large amounts of waste water</td>
</tr>
</tbody>
</table>

Several companies have developed and patented methods based on hydrometallurgical processes, but few seem to have been tested on a larger scale (Binnemans et al., 2013), the Rhodia/Solvay process described in section 3.4 being an exception.

4.4 Miscellaneous

Different methods have been suggested and tested for products such as optical glass, glass polishing powders and cracking catalysts for the petroleum industry, but have not been tried on a larger scale. (Tsamis and Coyne, 2015, Binnemans et al., 2013)

The EURARE project, though being more focused on production from mining rather than recycling, is looking at extraction and separation using ionic liquids, improved hydrometallurgical methods and molten salt electrolysis, as well as electro-recovery solutions from ionic liquids. They hope that ionic liquids could replace the usual acid leaching and thereby reduce both the use of hazardous chemicals and the amount of waste produced. (EURARE Project, 2015)
The Canadian company Orbite Aluminae Inc. has patented a series of processes for recovering, among other things, REE from the red mud produced in the Bayer process for aluminum production. (Orbite Aluminae Inc., 2015)

The Belgian company Comet Traitements uses a bio-hydrometallurgical process developed together with the University of Liège to recover several metals from mixed, shredded metal scrap. The process uses bacteria with the main function of regenerating iron(III) ions, which act as oxidants, in the sulfuric acid solution used in the process. (Comet Traitements, 2012) In the EU project Biolix this process will be further developed to include, among other things, REE recovery. (Comet Traitements, 2014)

Methods such as liquid membrane extraction and chromatography have also been suggested and tested on laboratory scale. (Forsberg, 2014, Helling and Strube, 2013)

**5 Challenges**

The main challenge of REE recycling is usually the presence of contaminants in the feedstock. (Binnemans et al., 2013, Tsamis and Coyne, 2015) For example, electronic waste has a very complicated composition with numerous contaminants; common permanent magnets contain 72 weight% Fe, which in many suggested REE recovery processes cannot be recycled into a sellable product. (Binnemans, 2013) In many cases extensive pretreatment is required to extract a fraction from which REE can be recovered efficiently. (Schüler et al., 2011)

Other challenges are deficiencies in the waste collection, technical difficulties such as separating neodymium magnets from the items that contain them and a lack of incentives such as regulations or a sufficiently high and stable price level. (Binnemans et al., 2013, Schüler et al., 2011) Another problem is that much used goods containing REE are exported to developing countries, reducing available feedstock for the countries that have the technical infrastructure necessary for the recovery processes. (Schüler et al., 2011)

Most suggested recycling methods demand large amounts of energy and chemicals. They often require the use of hazardous chemicals such as strong acids, NaOH and HF, which often cannot be recovered from the process and instead end up as chemical waste or as pollutants in effluent water. (Tsamis and Coyne, 2015)

**6 Possible Synergies**

By focusing on recycling the REE that are in strongest demand the so-called balance problem, which is the discrepancy between the demands for the different REE and the composition of said REE in deposits, could be reduced. Currently, there is a lack of REE such as Dy while large reserve stockpiles of other REE that are in less demand are built up. (Binnemans et al., 2013)

REE recovery could make it economically viable to treat certain industrial waste products that are currently stockpiled or landfilled, such as red mud from aluminum production. Another example would be Swedish LKAB’s large stockpiles of apatite, which contains phosphate, REE and magnetite, where the company is currently looking at possible future processes together with the Swedish university LTU. (Magnusson, 2011)
A very special case would be Gd used in MRI contrast agents, which, after leaving the body, can pass through the sewage treatment plants to pollute surface- and groundwater. Therefore a recovery process might be desirable for reasons of environmental protection rather than the possibility for reuse. (Binnemans et al., 2013)

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