CHALMERS

The Product Chains of Rare Earth Elements

Used in Permanent Magnets and NiMH Batteries for Electric Vehicles

Master of Science Thesis in the Master Degree Programme

Industrial Ecology - for a Sustainable Society

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Abstract

This master thesis will address the topic of rare earth metals and their product chain from early mining processes, through refining to final products and recycling. The analysis will cover the global product chain and its different actors.

Rare earth metals consist of 17 elements of the periodic table; the 15 lanthanides, scandium and yttrium. Despite their name, these elements are not rare, but quite abundant all over the earth's crust. Nevertheless, their concentration in the deposits is often very low and they are difficult to extract and refine. The rare earth metals are similar in their characteristics and can be used for many different applications. Rare earths are commonly used in green technology since their unique properties can save weight and increase efficiency in products such as light bulbs, generators in wind power plants, and in different parts of hybrid and electric vehicles.

The focus in this report will be on the product chains of the rare earth metals used in permanent magnets and batteries used in hybrid and electric vehicles, these are: neodymium, praseodymium, lanthanum, dysprosium, cerium and terbium. In nature these elements do not occur as metals and many complicated processes are needed to convert them into metals. The product chain starts with the mining and separation processes, next comes further refining and separation processes, and then production of rare earth metals and alloys before they can be shaped into parts in a final product. In total China has more than 95% of the global market for mining and separation processes for rare earth metals, also the production of rare earth metals and alloys occur to a large extent in China.

The production of most permanent magnets also takes place in China, but there is also production in Japan, Finland and Germany. Japanese car manufacturers have most of their parts produced within Japanese borders, which means that most permanent magnets used in hybrid and electric vehicles are produced in Japan. The same is true for the NiHM batteries, about 95 % of those that are inside these vehicles today are produced in Japan by Japanese manufacturers.

The markets for green technology seem to expand, creating an increasing demand for rare earth metals. To meet the demand with a larger supply there is need for solutions such as new mining projects, reopening of closed mines, or recycling and recovering of rare earths from scrap products and mine tailings.

The urge for more supply of rare earth metals and also rising prices presents a good incentive for recycling and recovering different rare earth metals from discarded products. These recycling and recovering processes are technically and often economically very demanding. Today there are processes that could recover rare earths with a high level of purity, but the problem is often the huge costs for the processes as well as handling of waste chemicals and materials that might be toxic. New processes will have to be developed. There has been research for new processes, and recycling/recovering plants are planned to be constructed in Japan as well as other countries.

This report will also look at the potential for having parts of the rare earth product chain in Sweden, since the country has both the physical resources and also metallurgical knowledge. With this in mind we discussed the possibilities of eventually operating the processes in the product chain in Sweden, and aspects of this scenario.

Preface

This master thesis was written at ESA, Environmental Systems Analysis, at Chalmers University of Technology. Henrikke Baumann, associate professor at the department of ESA has been our supervisor. The making of this master thesis has been the final task of the Master program Industrial Ecology – for a sustainable society. Therese Eriksson has previously studied the bachelor program Industrial Economy at Chalmers University of Technology, and David Olsson has a Bachelor of Science in Mechanical Engineering also at Chalmers.

The idea of this master thesis came from Magnus Karlström who writes a daily newsletter to people within Swedish automotive industry. The newsletter covers a lot of news about the vehicle manufacturing industry and rare earth metals is a hot topic among vehicle manufacturers today since hybrid technology uses them frequently in different applications.

The thesis outline was addressed to map the global product chain for these rare earths frequently used in hybrid vehicles and describe the different steps from mining to potential recycling. Also a future scenario with possible stages of the rare earth processes located in Sweden would be discussed. In order to map the product chain our goal has been to collect and analyze information from different available and trustworthy sources and analyze it to get a perspective over the whole product chain globally.

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1 Introduction

Once upon a time there was a Chinese fishing boat. One day in September 2010 the fishing boat was out fishing on the South China Sea, when suddenly it collided with a Japanese coast guard vessel. The Japanese coast guards told the Chinese fishermen that they were trespassing Japanese water. Then the Japanese coast guards took the captain of the fishing boat into detention. This made the Chinese government upset. They told the Japanese to let go of the captain. But the Japanese would not listen. Then China decided to punish Japan by stopping all exports of rare earth elements to Japan. Since Japan is a country with much industry and little natural resources they got really scared. How would they now get raw material for their companies producing things like hybrid cars and electronics?

The moral of this story is: do not buy all your eggs from one basket!

The story above is perhaps not exactly what happened, but an event like this was said to be the reason why China stopped exporting rare earth elements to Japan for some time in the fall of 2010. That export stop worked as a wakeup call to the world, because China controls more than 95% of the global supply of rare earths today.

Rare earths are being used in many applications today. Several “green” technologies, such as hybrid electric vehicles, wind power, low energy light bulbs, biofuels, etc., depend on them. Today China stands for more than 95% of the world supply. This has not always been the case. USA used to be the dominant supplier between 1950s and 1980s, but because of lax regulations and low costs for industry in China they have now taken over the dominance. This has become a power-broker for China, who is “threatening” to restrict and raise taxes on rare earth export. Leaving the rest of the world in anxiousness for future supply to, what seems to be, a growing demand. Though in all fairness, China will probably need more rare earths for domestic use since they are planning on e.g. expanding wind power and having more electric vehicles on the roads, also there is concern that the resources will be exhausted within a few decades with recent production rate (in case of no new discovery of deposits). However, the concern of supply shortages has compelled many nations and companies to start planning ahead and think of strategies to avoid deficits.

Rare earths are actually not rare, they can be found all over the earth’s crust, but they are difficult to extract and separate, and are usually only found in low concentrations. There are many mining projects exploring feasibility of production outside of China, and the question is if they will be operable in time, before a supply crisis might strike. There are also large amounts of rare earths in-use, which are potential sources of supply. Today there is practically no recycling of these elements, since the technology for it is missing.

1.1 Aim and objectives

The aim of this report is to analyze the global product chain of the rare earth elements that are used in permanent magnets and NiMH batteries in hybrid and electric vehicles. This analysis will follow the elements from the procurement of raw material to the end in the final product and then possibly their looping back through recycling. The rare earth market has been a hot topic in the media lately, due to the global trade and political issues around these elements. The outcome of this report is supposed to be used as information basis of a daily newsletter that is sent out to people within Swedish commercial and industrial life. The report should provide an overview of the present situation, and to some extent speculate about the future, but it will be up to the reader to make up her/his mind about the future of the rare earth industry and market. The research questions that have lead this report are:

- What processes and actors are involved in the product chain?
- Where are those processes and actors located in the world?
- Could the rare earth elements be a constraining factor for the hybrid or electric vehicle?

1.2 Thesis outline

The structure of this report is described below. This is meant to give guidance to the reader for what to expect from each chapter.

Chapter 2 explains how the methodology of this report was configured, combining four tools from environmental science. The reader will also be introduced to the rare earths that will be the focus in this report. And finally, a description of how the information and data for this report was collected

Chapter 3 will give the reader background information to the subject of this report: what rare earths are, why they are important, in what applications they are used and why there is concern for supply shortage of them.

Chapter 4 reviews the product chain for rare earths both for permanent magnets and NiMH batteries. The chapter will deal with the processes involved in the product chain.

Chapter 5 presents the organization of the product chain; its included actors, their geographical locations and connections will be mapped. To some extent mass flows will be presented in this chapter.

Chapter 6 will discuss the possibility of having the whole product chain in Sweden.

Chapter 7 will discuss the results from chapter 4, 5 and 6 regarding the aim of the report.

Chapter 8 will conclude chapter 7 in short sentences.

1.3 Abbreviations and concepts

This subchapter will explain some of the abbreviations and concepts that will be used in this report. The chapter can be used as a dictionary when reading the following text.

BGS – British Geological Survey – a public sector organization responsible for advising the UK government

CIS – Commonwealth of Independent States

EV – electric vehicle

HEV – hybrid electric vehicle

HREE – heavy rare earth elements

Hydrometallurgical processes – chemical processes to recover metals from ore or recycled products

LREE – light rare earth elements

MEP – ministry of environmental protection

MOFCOM – ministry of commerce in China

Misch metals – a mixture or alloy of different rare earth metals

PEV – pure electric vehicle

RE – rare earths – short for the 17 rare earth elements

REE – rare earth elements – the elements in their natural form

REM – rare earth metal – after processing the elements into metals

REO – rare earth oxide – after separating the metals from the host mineral, the oxide usually contains 60-70 % pure elements, still a mix of several rare earth elements

Reserve – the part of a (natural) resource that is economically recoverable with existing technology

Resource – an entity of limited availability

TREO – total rare earth oxides – the term includes all rare earth elements in oxide form, commonly used when talking about mining and production

USGS – US Geological Survey – a governmental science organization

2 Method

2.1 Combining four tools into one method

For this report inspiration was taken from four different tools: life cycle analysis, material flow analysis, commodity chain analysis, and technology assessment. These are different tools that has contributed in different ways and helped us form a method exactly fit for our purpose. None of the tools have been used outright, therefore this part will explain how the tools have been used and in what part of the work they have been used, see also figure 1.

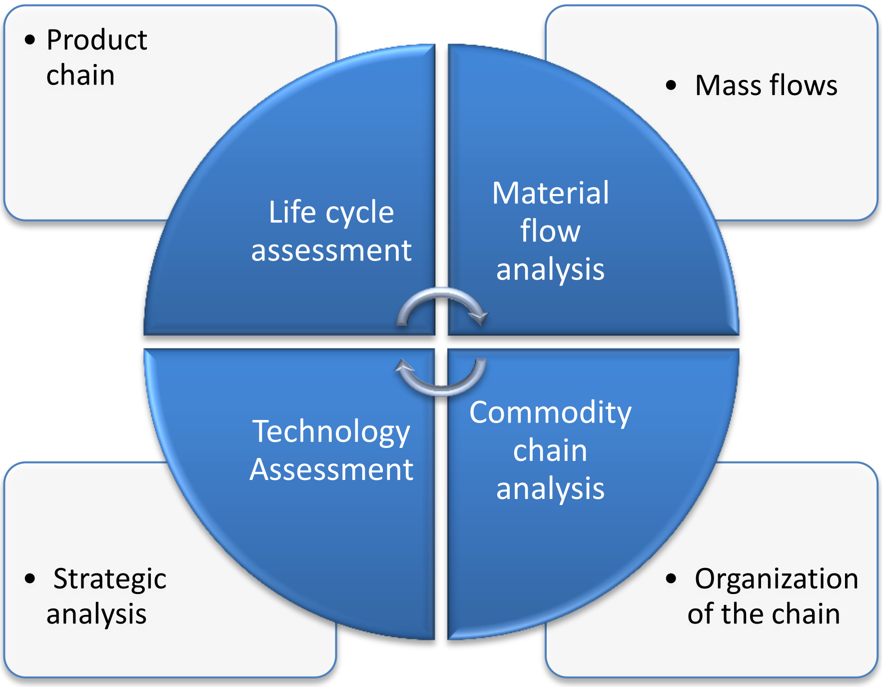


Figure 1 A visual description of how our method is composed

2.1.1 Life cycle analysis

In a life cycle analysis (LCA) the environmental impacts during the entire life cycle of a product is assessed, from procurement of the raw material to disposal of the used product. The idea is to measure the amount of used natural resources and pollution a product is responsible for and then to assess the consequent environmental impacts. An LCA can be used either to see where in a product's life cycle there might be environmental problems, or to compare products that provide the same function. In an LCA there needs to be clear boundaries to the system that will be assessed and what processes to include. It is not necessary to look at the whole life cycle of a product, in some LCAs the user and disposal phase might be excluded, but there needs to be definition of the boundaries for the results to be useful. The system boundaries depend on the purpose of making the LCA and the question that is to be answered. However, the system boundaries in this case only include different processes, geography and time is usually not included. (Baumann and Tillman, 2004)

The life cycle thinking was used in the initial stage of making this report; the perspective was used when mapping all processes in the life of rare earths, from mining to disposal. However, the aim of the report is not at all to assess the environmental impacts of these processes. Therefore there will not be many resemblances with an LCA and the results of this report, except the life cycle perspective. This report, as opposed to LCA, includes the geographical pathways, and their mapping is of greater importance than the environmental impacts, which will only briefly be mentioned.

2.1.2 Materiel flow analysis

MFA is a tool to systematically assess the flows and stocks of a material or substance in a system defined with boundaries in space and time. The idea is based on conservation of matter within the system; all that goes in will either stay in the system or exit from it. Within the system the pathways that connect all the intermediate and final sinks are mapped to track all the material that goes in, and detect where it ends up. Flows that enter the system, passing its boundaries, are called inputs, and those exiting are called outputs. An MFA is a quantitative analysis that uses mass balance to check that all inputs correspond to the stocks and the output. (Brunner & Rechberger, 2004)

Our approach to map the product chain of rare earth metals was largely influenced by the Material Flow Analysis (MFA). The aim of this thesis was to map the global flows of rare earth metals. However, in a complete MFA, all the flows of the material is mapped, whereas this report will only follow those elements' pathways that end up in permanent magnets and NiMH batteries for electric vehicles. The whole chain of processes involved in the life cycle of these products, from mining to final product (and also recycling possibilities), will be mapped to the extent possible. But since there are too many different manufacturers, in some parts of the chains, those that are located in the same country, e.g. China will be “lumped together”. This will be clear to the reader in the parts of the report that this concerns. Also, an MFA is a quantitative tool, whereas here the analysis will be of a more qualitative nature since it would be too difficult and time consuming (not to say impossible) to find the exact numbers and pathways. A full quantification would also not be required to fulfill the aim of this report, but some quantification will be made to show the dimensions of some of the flows and stocks (e.g. mining rate and the in-use stock). The unit that will be used is rare earth oxide (REO), which is the total amount of the rare earth elements in a mineral. REO does not say what share an individual rare earth elements has in the oxide, that differs depending on location of the mine and type of mineral mined. Our system's spatial boundary will be the earth. The temporal boundary will be a year; this is mostly because data on supply and demand is usually given on a yearly basis. Different years might be reviewed to enable comparison and trace trends.

2.1.3 Commodity chain analysis

The commodity chain analysis (CCA) is an extension of supply chain analysis that also takes social and societal aspects into account. In a CCA the task is to understand what social values a commodity has across its chain of production, from raw materials extraction to final product and what it is that drives each actor to be a part of that chain (Boons and Howard-Grenville, 2009). In this report we will not look at social values, but we will look at different actors along the product chain. This will be a complement to the features that we have used from MFA, since we also want to know who are participating along the chain, driving the material flow, and how the chain is organized.

2.1.4 Technology assessment

The method for this report will to a large extent resemble a technology assessment (TA), in the sense that a technology with possible materials constraints will be analyzed. A TA is a concept which can use many tools to assess concerns of the development of a technology: economical, environmental and social. It is used to support decisions on strategies and policies. The concept is quite broad and there are several types of TA's, but the overall aim is to forecast the impacts and effects of technological change, so that they can be included in decision making. Van den Ende et al (1998) distinguishes four different types of TA:

- Awareness TA – a forecasting approach to give warning about impacts and consequences of technological developments.
- Strategic TA – to be used as a support for actors to make decisions about strategies or policies in regard to specific developing technologies.
- Constructive TA – to influence the development of a technology in a direction that is desirable for the society.
- Back casting – to create a desired future scenario and then develop technology that will lead to that scenario.

The approach that is most fit for this report is the strategic TA. The use of such an assessment is to see how sustainable a technology would be in a longer term perspective, with developments, extensions and/or modifications. This report aims at investigating the question of possible materials constraint for the currently most used technology in the motors and batteries of electrical vehicles. In order to do so, the report needs to look at resources, other applications, and recycling of the materials in question. However, the aim of this report is not to predict the future and give an answer for the sustainability of these technologies, but rather to provide a view on the present state of the supply and demand of materials used in the technologies the way they are today. It will then be up to the reader to judge if sustainable.

2.1.5 The method of this report

Working on this report has involved a lot of mapping. As in LCA we have mapped all the processes in the making of the specific products, from “cradle to grave”, as in MFA we have mapped how the elements flow on a global scale, and as in CCA we have mapped the actors that are involved in the product chain. This will then make up basic data for a TA inspired discussion about selected rare earths.

The product chains used in this report is made up of eight respectively seven steps, as shown in chapter 4. For each step in these chains the involved processes and actors will be described. The quantitative flows and stocks in the chains will not be balanced; rather they will in some cases be estimated, to give the reader an appreciation of the volumes. Geographical sites and flows will also be described, to provide an understanding of where in the world the different processes in the chain takes place. The actors in the chain will be briefly presented as well as the relations and cooperation between them.

The perspective in this report is on the product chain. This report will provide a snapshot of a product chain that potentially is about to change. By using the information that is provided the reader will have some knowledge about the present situation to easier understand the implications for future changes.

2.2 The selection of rare earths in this report

In this report we are focusing on a selection of rare earth elements that are used for two specific applications. Permanent magnets can contain the elements: neodymium, praseodymium, dysprosium and terbium, and the NiMH batteries contain lanthanum, praseodymium, neodymium and cerium. However, in the first parts of the product chains it is very difficult to distinguish individual elements, since rare earths always exist together in a host mineral. They are quite difficult to separate, so this is made in the third step of the product chains (presented in chapter 4). Any data on amounts of REO does not specify the amount of individual elements, since this differs between locations and minerals. Distribution of the individual elements in the ore from some of the different mines that are in or close to production can be found in the appendix.

2.3 "Speculations" about a possible product chain in Sweden

Chapter 6 of this report is of less scientific degree, as it contains speculations from us along with consultations with some experts within the area of metallurgical industry and recycling in Sweden. The chapter prospects future possible scenarios for Sweden as a participator in the global and domestic product chain for rare earth metals. Most scenarios are based on the fact that Sweden is a well-developed country when it comes to mining of metals such as, iron, copper and silver, and also the metallurgical industry with separation, refining, handling and recycling of such metals. For these reasons it could be interesting to speculate in the possibilities of future participation in the product chain. The information and speculations in this chapter is gathered through telephone conversations with people at Rönnskärsverket (which is a recycling plant for steel, iron and copper and a part of the company Boliden AB), Höganäs AB (which is a company specialized in iron and metal powders) as well as professors at University of Luleå, LTU, and Chalmers University of Technology, Gothenburg. The future scenarios mentioned in the chapter is therefore only suggestions of possible acts of the product chain that Sweden might be able to participate in since we do have knowledge within many other metallurgical areas with similar aspects as for the product chain of rare earth elements.

2.4 Collection of data and information

For this report different sources of information have been used in different phases of study. Firstly, to get a sense of the field, information was sought in newspapers, blogs written by experts in the area, governmental websites, home pages of nongovernmental organizations, and websites of companies all the way from mining companies to car manufacturers, encyclopedias and also searches on youtube. This gave a wide perspective on the area, including basic facts, political issues, technological developments and the race for production of rare earth elements. In a second phase the information search was more focused as the aim of the report had become clearer. But still, the same media was used. However, starting to know the area and different actors in and around the chain of rare earths, the sources were evaluated more thoroughly for reliability.

Some of the companies we were looking at provided useful information on their websites and in their annual reports; others were contacted by e-mail or phone calls. A few interviews have been held, in order to enable some discussion with valuable contacts. For chapter 6 there was not much published information to be found, instead experts (see chapter 2.3) was contacted to tell about their thoughts, opinions and the knowledge they had in their area.

The aim of this report is to provide a picture of the current status of the product chain of rare earths. In order to get the most updated information and latest news, internet sources were used to a large extent. The reliability of internet sources is always dangerous ground, which we are well aware of. Therefore it is important that the reader is aware of this and also reads this report with that in mind. We have valuated our sources and only used the ones that we have found reliable according to the

CARS Checklist (Credibility, Accuracy, Reasonableness, and Support). More information about this checklist can be found at the webpage Virtual Salt (http://www.virtualsalt.com/evalu8it.htm) and was recommended in the Chalmers course Assessing Sustainability Assignments in Q1 2010. In most cases the information has also been double checked with other sources; if several sources state the same information, chances of it being correct increases. But when referring we have chosen the one source that we found most trustworthy. In some cases, e.g. chapter 3.2, different sources gave different answers, but that is mentioned in the text.

3 Description of rare earth elements

This chapter will explain shortly what rare earth elements are, how they are produced, and in which applications they are needed. There will also be a part concerning the environmental impacts of their production; since they are used in so many green technologies it is important to also be aware that there are environmental consequences associated with them as well. The end of the chapter will lead the reader to the focus of this report: rare earth metals used in electric vehicles. Note that when this report talks about electric vehicles, hybrids are also included. The product chains that will later be analyzed in the report will be presented, and also the concerns related to their functioning.

3.1 Context

Since the first rare earth elements were discovered outside Stockholm in the late 18th century their unique qualities has become important in many technologies. Several of the "green" technologies today use rare earths, because they can increase energy efficiency and decrease weight in many applications. When they are used in windmills they help produce CO_2 free electricity, and when that electricity is used to drive electric vehicles we can avoid using fossil fuels. This report will focus on those elements that are used in the motor and battery of hybrid and electric vehicles. Later in the report they will both be referred to as electric vehicles, since they partly of fully are driven by electricity.

The rare earth production has, up until now, had a rising trend. The world demand for rare earth elements was in 2010 approximately 134 000 tons (Humphries, 2010). That is an 8% increase from the demanded 124 000 tons in 2008, which in turn is a 45% increase since 2003, the biggest importers are Japan, USA, Germany, Austria and France (China can still supply their own needs as well as others') (BGS, 2010). The applications are many: magnets, ceramics, phosphors, fluorescent lamps, lasers, glass coloring, catalysts, and more. Products containing rare metals are for example: electric vehicles, hard drives, wind turbines, nuclear reactors, laptops, mobile phones, and TVs. They are also important for military uses, e.g. smart bombs, missile guidance systems, jet fighter engines, mine detection systems, and communication systems (Humphries, 2010).

Figure 2 shows some of the other applications for the REEs that are of significance for the aim of this report. These other technologies can be considered as competing technologies; competing for the same material. When forecasting future demand and availability of the materials needed in permanent magnets and NiMH batteries the growth (or decline) of these other technologies must be considered.

Lanthanum	Neodymium	Praseodymium	Dysprosium	Terbium	Cerium
•Catalytic converters	•Hard disks	•Motors	•Lasers	•Fuel cells	•Catalytic converters
•Fuel additives	•Mobile phones	•Fibre optics	•Nuclear reactor rods	•Flourescent lamps	•Glass production
•Glass	•Loudspeakers	•Coloring glass	•Hard disks	•Low energy lighting	•Steel
•Fuel cells	•Magnetic refridgeration	•Carbon arc lights	•Dosimeters	•Solid state devices	•Carbon arc lights
•Steel	•Lasers				
•Capacitors					

Figure 2 Different applications for the rare earths focused on in this report

Rare earth elements have been a hot topic in politics and media lately, especially after the temporary Chinese export halt to Japan in the fall of 2010. The demand for these elements have increased substantially in the last 15 years, and there are strong indications that it will continue to rise as the technologies using rare earths, perhaps most importantly hybrid- and electric vehicles and wind power turbines, are growing (BGS, 2010). However, it is uncertain if the supply will meet the demand in the future. The fact that China dominates the production of these metals so strongly makes the rest of the world absolutely dependent on their exports today. Lately China has cut their export quotas; in 2010 the export had decreased by 9.3% compared to 2009, and in the first half 2011 the export is supposed to be 35% less than the same period in 2010 (China Mining, 2011). This cannot be explained by decreased production in China, because the output quota is set 5% higher in 2011 than previous year (china.org.cn, 2011). There are perhaps many reasons why China is cutting the export, and it is not within the scope of this report to deeply investigate this matter. However, there are indications that China will be using larger amounts of rare earths themselves in the future, which would mean less to export. The Ministry of Commerce (MOFCOM) in China recently posted news on a drafted plan, made jointly by four Chinese ministries, that suggests that during 2011-2015 China should have the capacity to produce one million non-fossil fueled vehicles, out of which 50% should be hybrid or electric vehicles. Until 2020 this number should increase to 5 million, since the statement says that China aims to be the leading nation in the “new-energy vehicle” sector. (MOFCOM, 2011a) Assuming that the same technology will be used in these vehicles as today, this means that an increased production of electric vehicles will consume large amounts of rare earth metals. China also plans to have more wind power in the future, which is a technology that in some cases uses large amounts of the same rare earths as electric vehicles.

There are no certain estimations for future demand for rare earths. Mark Smith, the CEO of Molycorp Minerals, anticipates a demand exceeding 200 000 tons by 2015 (Smith, 2010), which is an estimation that he shares with several exerts in the field, who suggests roughly the same number. The Chinese rare earth expert Chen Zhanheng, The Chinese Society of Rare Earths, predicts a 15% increased demand annually in good economic conditions. The demand outside of China would be 80 000 tons, according to him (Zhanheng, 2011b). Something that is certain is that the demand for the individual elements will vary a lot. Smith forecasts that the elements most likely to be in short supply vis-à-vis the demand will be neodymium, europium, terbium, and dysprosium.

On an average the prices of rare earths has increased significantly during the last years. There is no recognized exchange for rare earth elements, they are usually bought through trading companies and their prices are highly influenced by the producers (BGS, 2010). The price of rare earths is affected by several factors, e.g.: the different elements are valued individually (the HREE are usually more expensive since they are less abundant), the prices fluctuates depending on the prevailing demand, and the elements are difficult to separate and therefore the purity level also affects the price. According to MOFCOM (2011b) the prices for two of the metals used both in permanent magnets and NiMH-batteries, neodymium and praseodymium, have increased by 125% of previous year in 2011. For dysprosium, also used in the same applications, the increase was 104%. China will also put a higher tax on mined rare earths, starting in April 2011, which will mean higher production costs.

3.2 Elementary information

“Rare earth elements” is a collective name for 17 chemical elements including scandium, yttrium and the 15 lanthanides occupying numbers 57 to 71 in the periodic table (see figure 3). These elements often occur in the same ore and have similar properties: soft, malleable, ductile and reactive (especially at elevated temperatures) (Gupta & Krishnamurthy, 2005). Most of the elements are also magnetic. The lanthanides are usually divided into two groups: light rare earth elements (LREE) and heavy rare earth elements (HREE). The LREEs are La-Eu, and the HREEs are Gd-Lu (BGS, 2010). Yttrium is usually considered to be a HREE (Gupta & Krishnamurthy, 2005). Scandium is a bit more uncertain since it is not always considered a rare earth at all (to confuse the reader even further, the opinions on which elements are considered rare earth elements also differ between experts, but in this report we have chosen to believe the opinion of the majority, and the latest information). The definition of which elements belong to which subgroup differs in the literature, and sometimes the elements are divided into three subgroups, in that case samarium to dysprosium are called medium rare earths (Gupta & Krishnamurthy, 2005). The lighter elements are usually more abundant than the heavy since they are more incompatible, also elements with even atomic numbers tend to be more abundant in the earth's crust. (BGS, 2010)

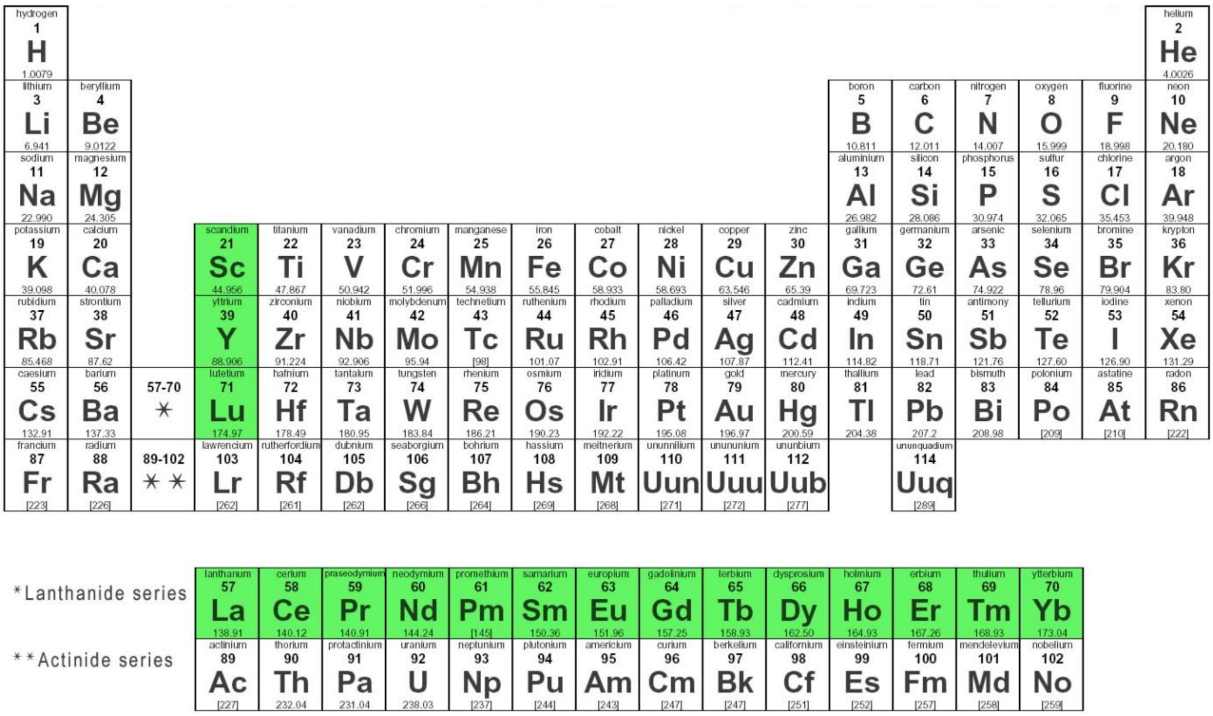


Figure 3 The periodic table with the rare earth elements highlighted (BPC, 2010)

Despite their name these elements are not really “rare”. They can be found in various places around the Earth's crust. Cerium is the most abundant rare earth, also yttrium, neodymium and lanthanum has abundance comparable with common industrial metals such as chromium, copper and nickel. The least abundant rare earths (tellurium and lutetium) are still nearly 200 times more abundant than gold. (USGS, 2011) The problem in producing these metals is that they are usually found in very low concentrations, which often makes the findings economically unfeasible for mining. Since they are chemically similar to each other they can easily substitute for one another in crystal structures, they usually occur together in the same mineral and are relatively difficult to separate. (BGS, 2010)

So, in spite of their name, there are plenty of rare earths and they do exist in many places all over the world.

In nature the rare earths do not occur as metals, but as a part of host minerals where they substitute for ions. There are at least 200 minerals that contain rare earths, but only a few are used for rare earth production, the most common ones are monazite, bastnäsite, and xenotime. (BGS, 2010) These three usually contain approximately 65-70% REO. Monazite is the single most common rare earth mineral (USGS, 2002). It has the formula (Ce, La, Nd, Th)PO_4. As can be seen in its formula it contains radioactive thorium, and also uranium, which can present a problem for mining if the weight percent is high. It can be found in many different environments, from rocks to beach sands. Monazite contains mostly LREE, and low concentrations of HREE. Bastnäsite also contains mostly LREE, but very low concentrations of radioactive elements, which is good for mining. This is the main rare earth mineral in e.g. the large deposits in Bayan Obo, China, and Mountain Pass in California, USA. Xenotime is richer in HREE than the other two, and has low to no content of the radioactive elements. It is found in heavy mineral sands in e.g. Malaysia and Brazil. (Gupta, 2005) Table 1 below shows the content of rare earth oxides, thorium and uranium in these three minerals. Rare earth elements are also produced from ion adsorption clays. These clays are especially rich in HREE, but they are only known to exist in China and Kazakhstan, since they require special weather and environmental conditions to form, which is the reason why China is the main supplier of HREE today. (USGS, 2010)

Mineral	Formula	REO (wt%)	ThO_2 (wt%)	UO_2 (wt%)
Monazite	(Ce,La,Nd,Th)PO_4	35-71	0-20	0-16
Bastnäsite	(Ce,La)(CO_3)F	70-74	0-0.03	0.09
Xenotime	YPO_4	52-67	--	0-5

Table 1 The content of REO, ThO2 and UO2 in the three most commonly mined RE minerals (source: USGS, 2010)

Since the concentration of rare earth elements in the host minerals are usually very low, the feasibility of mining them economically is often a problem. However, the rare earth minerals are often found near other minerals containing e.g. iron, copper, uranium, tantalum, and zirconium. The rare earths can then be mined as a co-product (the costs of mining and production are shared by the main and co-product) or a by-product (the costs of mining and production is covered by the main product). (Gupta, 2005) As prices for rare earth metals are increasing, more mining companies are starting to realize that their tailings, containing rare earths, could be valuable. That is the case for LKAB in Sweden, who are now investigating possible future processing of tailings from their iron mining.

3.3 Environmental issues

The environmental consequences of the rare earth metal production are many, ranging from mining to separation: e.g. energy use, chemical use, land destruction, waste production and radioactive waste. One of the main reasons why China was able to take over and to dominate the world production of rare earths is that the regulations was lacking or was so much slacker than in other countries that historically has been large producers of rare earths (e.g. USA and Australia), which meant that they could offer lower prices (Houses of Parliament, 2010). In China problems such as soil erosion, water loss, and pollution of soil and ground water has led to destruction of much land area around the mines because of insufficient control. The extraction of rare earth metals is energy intense, and since most of it takes place in China where coal power plants produces a large share of the energy it creates emissions. Up till now there have not been limits for emissions or production, and in the south of China there have also been problems with illegal mining. (Zhanheng, 2010) The smuggling of rare earths has been a huge problem in China. In 2008 as much as 20 000 tons of rare earths was reported to have been smuggled out of the country illegally, which was a third of the total exported rare earths from China that year (Hurst, 2010), numbers for illegal mining are naturally just estimations, not facts. Illegal mining means that the resources will be depleted faster, and that this mining is operated without any regulation at all which has large implications on the environment and also affects the prices of rare earths. In 2011 the Chinese government started to take action for protecting the environment and the resources, and thwart smuggling. This includes setting new standards and rules for the rare earth industry, e.g. lowering the limits for the allowed emission levels, limit production quotas, encouraging mergers and acquisitions, and reducing the number of mines and processing plants. Over all China wants to increase the governmental control over the rare earth industry and consolidate it; in Baotou, where the largest rare earth reserves in China are, the number of producers have been reduced from 150 to 18 during the last years. New licenses for rare earth mining has not been issued since 2006, and to fight illegal production those who produce less than 8000 tons a year will have to close or merge with another producer. (MEP, 2010) The new and stricter environmental standards in China will come in force in the second half of 2011, but the companies will have two years' time to upgrade their technology before they are banned from the market. This will force many companies to invest more in environmental protection, and smaller companies might be forced to merge with bigger ones to cope with the costs. The market is concerned that the prices of rare earths from China will rise because of this. (China Daily, 2011)

3.4 Rare earth elements in hybrid and electric vehicles

Rare earth elements are used in many parts of an electric vehicle, e.g.: motors, NiMH batteries, windows, glass, catalytic converters, electronic equipment and more. However, this report will focus on the permanent magnet motors and the NiMH battery. The world's most sold hybrid vehicle model, Toyota Prius, uses somewhere around 10 kilos of rare earths, see table 2.

	Permanent Magnet	NiMH Battery
Lanthanum	-	5400 g
Neodymium	300-600 g	900 g
Praseodymium	75-150 g	1800 g
Dysprosium	Smaller amounts	-
Cerium	-	900 g
Terbium	Smaller amounts	-

Table 2 Rare earth content in the NdFeB permanent magnet and NiMH battery in a Prius (Sources: Bubar, 2011 and Maruo, 2011)

The permanent magnet in electric vehicles weights between 1 and 2 kilos, approximately 30% is neodymium (Bubar, 2011). The neodymium can partly be replaced with praseodymium; the alloy is then called didymium and contains ca 75% Nd and 25% Pr. To increase the temperature stability and coercivity of the magnet, smaller amounts of dysprosium or terbium can be added.

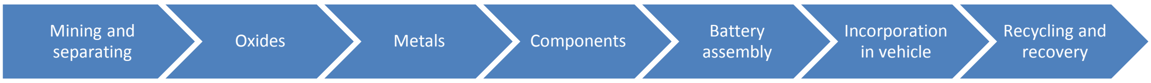
The NiMH battery in Prius vehicles has been improved over time and nowadays they are significantly smaller and lighter than they were when it was first launched in 1997. Approximately the battery pack weighs 37 kg today, the amount of rare earths in the anode material might be a little more than a quarter of that. The material in the battery is a lanthanum misch metal, the ratio between the included elements is: 60% La, 20% Pr, 10% Nd, and 10% Ce. (Maruo, 2011)

The Toyota Prius was the first hybrid vehicle to be mass produced. Since its lunching in 1997, more than 3 million Prius cars have been sold globally (Toyota, 2011). The Prius has been far more successful than any other car manufacturer's hybrid car model, so to estimate the number of hybrids sold globally since 1997, a little more than 4 million might be enough. The future outlook for hybrids and pure electric cars seems bright. However, it is difficult to say how many of these will use NiMH batteries, since Li-ion are expected to be the more popular choice in the future. Even Toyota will have to use Li-ion in their plug-ins, since NiMH is not good for PEVs.

Most commonly there are two types of permanent magnets. One of them is the Nd-Fe-B magnet, often referred to as neodymium magnet. The second type is the Sm-Co type magnet. The samarium-cobalt magnets were introduced in the 1970's and this lead to an expansion in the usage of permanent magnets. The intensified use of magnets increased knowledge and helped to develop another compound with even better magnetic characteristics, the neodymium type (Sastri, et. al, 2003). The characteristics of these two types are somewhat similar but the neodymium magnets have a higher magnetic energy density which makes it a better choice in wind turbines and hybrid vehicles. Due to the high energy density in permanent magnets, they often replace electromagnets in many types of applications (Sastri, et. al, 2003). This is due to the fact that no external energy source is needed to provide the magnetism.

4 The structure of the product chain

In this chapter the technical approach of the rare earth product chain is presented in order to explain the different stages. The first three steps are shared for both permanent magnets and NiMH batteries, and will be dealt with in subchapters 4.1 and 4.2. After that the two chains part and are dealt with in separate subchapters 4.3 and 4.4. Finally, they merge again in the last step, recycling and recovery, which is chapter 4.5.



4.1 Mining and Separation

The rare earth deposits around the world differ in nature which calls for different methods of mining and extraction of the elements. In general, the extraction can be either open pit mining or underground mining. The mined ore usually has a very low grade of rare earth content, sometimes as low as just a few wt%, therefore it is common that there is a facility (sometimes called a concentration plant) close to the mine to concentrate the REE and separate it from the gangue minerals, and possibly other products (BGS, 2010). In Bayan Obo, the district that has the world's largest production today, the open pit method is used for mining. The separation process contains grinding of the ore and separating through flotation with different chemicals (alkalis and acids). The concentrate then contains a little more than 60 % REO. The separation processes are usually quite complicated, and as mentioned different ores containing different minerals require specific methods. Leaching, electrostatic and magnetic separation, and filtration are other processes that can be included. The beach sands in India already have a very high concentration of REE and do not need any treatment in this step (Gupta & Krishnamurthy, 2005).

4.2 Oxides and metals

The oxides must be treated further in order to increase the RE concentration or to be used as metals. This procedure is very difficult since the oxides are very stable. In order to obtain more pure forms of rare earth metals the oxides have to be reduced, which can be done in different ways. The basic principle is to use a chemical reducing agent to remove the impurities. These processes are technically difficult and demands large amounts of electricity. The metals can after the initial refining stages reach a purity of around 98-99%, and then be further refined to increase purity with another half percent. The metals are often formed and sold as ingots which at later stages can be grinded into powders for further usage. (Gupta & Krishnamurthy, 2005)

4.3 Permanent Magnets

This subchapter will continue along the product chain and explain the technical steps from metal to magnet.

There are two different types of neodymium magnets. The ways of producing these two types of magnets are somewhat similar but have some differences. The sintered magnets are made from metallic powder which is processed and grained from metal ingots into a fine powder with a particle size smaller than ten µm. The powder is then magnetically aligned by a magnetic field and pressed in a vessel and then sintered in a sintering oven, where the powder melts and get the wanted shape of a solid magnet (Kuhrt, 1995). When producing bonded neodymium magnets, the metallic powder is mixed or capsuled with a binder of some kind and then molded into shape. The binder can be of many types, for instance polymers, nitrile rubber, vinyl, nylon, Teflon, polyester or thermoset epoxies (Buschow, 2001). This bonding makes the magnet more versatile according to shape and size and can then be used in smaller applications and in various shapes (Bauer, et al., 2010). However, the added binding material also decreases the magnetic energy density which makes bonded magnets less attractive in larger applications (Buschow, 2001). The produced magnets are when finalized assembled in a larger product, for instance a vehicle, motor, wind power plant or other devices.

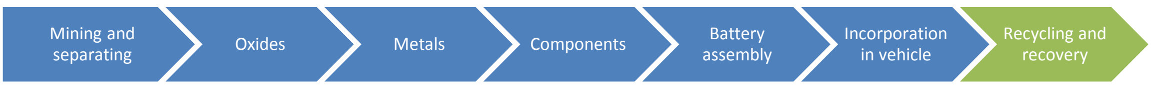
4.4 NiMH batteries

This subchapter will continue along the chain from metals to NiMH batteries.

The product chain of NiMH batteries continues, after the metal production step, with production of components. The metal used in NiMH batteries is a misch metal containing lanthanum (60%), praseodymium (20%), neodymium (10%), and cerium (10%) (Maruo, 2011). The next step is the assembly of the battery, which in the sixth step is incorporated into the vehicle. The exact processes for how to produce a battery will not be explained in this report.

4.5 Recycling and recovery

The last step in both product chains is the recycling and recovery step. Future-wise, this might be one of the most important steps since only small amounts of these products are recycled or recovered today.



The recycling processes regarding rare earth metals are quite new and still in the developing stages. Most processes are chemical but there are also possibilities to extract them mechanically and/or combinations of both mechanical and chemical processes. There are also possibilities to even reuse some products, like permanent magnets, with minor modifications (Lehner, 2011 and Ekberg, 2011).

Regarding NiMH batteries commonly used in cars, these types of batteries contain misch metals which for these batteries are a mixture of nickel and rare earths lanthanum, cerium, neodymium and praseodymium. These rare earths may be recycled through a procedure of mechanical and chemical separations (Ito, et. al., 2009). Ito et. al. along with Japan Oil, Gas and Metals National Corporation has come up with a method starting with mechanical separation of the battery to recover all the individual components after being crushed, and thereafter the components containing rare earths and other metals are chemically treated with dissolution and melting in order to separate the metals. The method was performed on two different types of batteries, cylindrical and prismatic shaped batteries, and includes many different steps that are quite advanced. The parts of the battery that are to be recycled are the anode and cathode parts. The method shows that it is possible to recover some of the rare earths in the batteries and that the purity of the recovered product was high and may be treated further in chemical stages in order to increase purity. However, the shape of the battery and how it is assembled can affect the efficiency of the recovery processes (Ito, et. al., 2009).

When producing neodymium magnets, especially for computer hard drives, approximately 50% of the used material is discarded as waste or scrap. This depends much on the fact that neodymium easily forms very stable compounds with other elements, of which oxygen is an example, and therefore the scrap cannot be recovered or reused directly without being treated first (Takeda, et. al., 2005). According to Takeda, et. al., 2005, there is a process to extract neodymium by using magnesium as an extraction medium. This liquor that contains the rare earths can later be treated with hydrometallurgical methods to extract the rare earths from the liquid. Similar methods as for the permanent magnets in hard drives and the NiMH batteries, can be used to recover rare earths from used computer monitors (Resende and Morais, 2010). There are some different methods for recovering rare earths from spent products but the basic method is to first perform mechanical separation and then further processing with chemicals through dissolution and refining processes.

5 The organization of the product chain

The product chain for the permanent magnets and the NiMH batteries are joined in the first three steps, since rare earth elements occur mixed together in their host mineral. But after the separation and refinement steps they part. This chapter follows this by presenting the first three steps in separate subchapters and then there will be two subchapters, one presenting the rest of the product chain for permanent magnets and one for NiMH batteries. The chapter will end with a subchapter about recycling, where the elements are again joined for a loop back into the product chains.

5.1 Mining and separation

This subchapter will provide an overview of the mining situation in the world: today, in the next three years and longer term. Beginning with the estimated world reserves and their locations, continuing in current production and existing mines, the chapter will later mention some projects for new mines. As mentioned in chapter 4.1 it is most common that separation takes place near the mine, by the same mining company.

5.1.1 Reserves and current production

According to the USGS (2010) the world industrial reserves of total rare earth oxides were an estimated 99 million metric tons in 2009. The country with the largest reserves is China, with about 36 million metric tons of REO. On second and third place comes the CIS and the USA, with 19 and 13 million tons respectively (see figure 4). However, the precisely accurate size of the world reserves is uncertain and changing. More recent estimations imply that they could be larger in 2010. Zhanheng (2011a) writes that Brazil, which according to the USGS only has a small share of the reserves, actually has the world's largest, about 52.6 million metric tons of REO. Nevertheless, USGS (2011) has not changed their figure for the Brazilian reserves in 2010. The figure for China's reserves has increased to 55 million metric tons. Figures for the other countries are unchanged or, as for Australia lowered in 2010 (see figure 5). The new figure for world total reserves of REO is then almost 114 million tons. One reason for widely differentiating figures is how the reserves are defined.

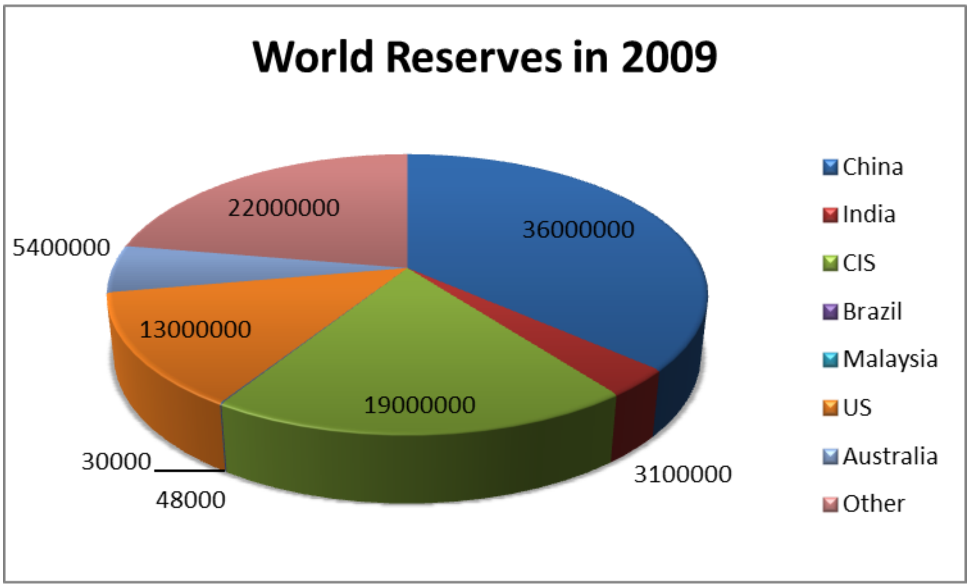


Figure 4 World reserves of REO in 2009 (source: USGS, 2010)

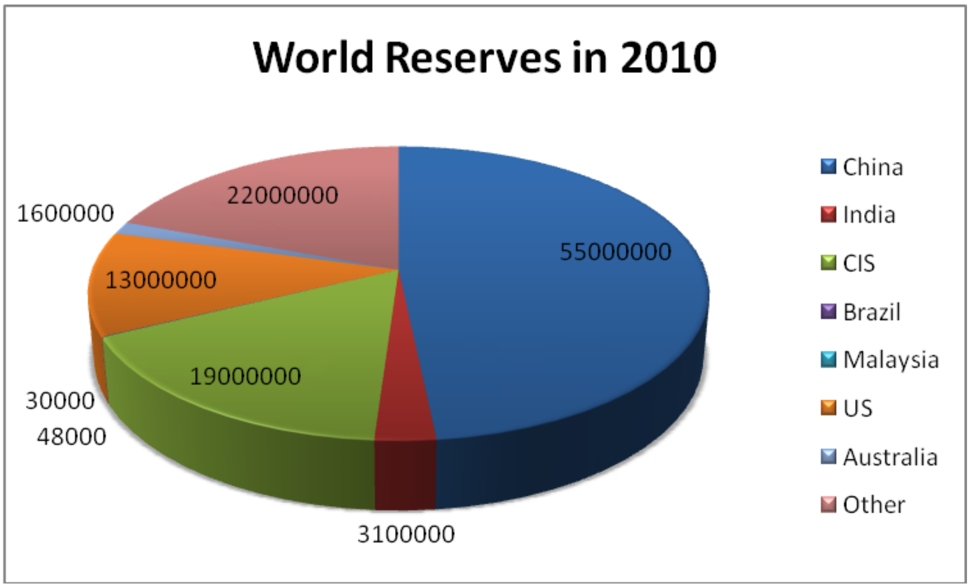


Figure 5 World reserves of REO in 2010 (source: USGS, 2011)

In the figures above, the “other” category includes Canada, Greenland, South Africa, Namibia, Mauretania, Burundi, Malawi, Vietnam, Thailand and Indonesia. The reserves are, in this data from USGS, defined as that part of the reserve base that could be economically extracted or produced with existing technology. Also these are the reserves known today, reserves are however not fixed; their size can change depending on prices and costs, technological development and new discoveries. There might still be undiscovered deposits in the world that could provide future production. One example of this is a newly discovered rare earth and niobium deposit in Afghanistan with an estimated value of $89 billion (Najafizada, 2011). Other examples will be presented in 5.1.3.

The production of rare earths is today mostly concentrated in China, where about 95% are mined, but historically the domination has changed between several countries. Until the 1940s the main suppliers of rare earths were India and Brazil, after that production also started in Australia and Malaysia. The Mountain Pass mine in California, USA, started producing in the 1950s, and during the 1960s to the 1980s USA were the main producers in the world. (BGS, 2010) China did not begin to produce rare earths until the 1980s, but because of lower production costs and less strict regulations they could sell their products much cheaper and possessed dominance as RE producer in just a few years (Haxell, 2002). The historical world production of rare earth oxides can be seen in figure 6 (Haxell, 2002).

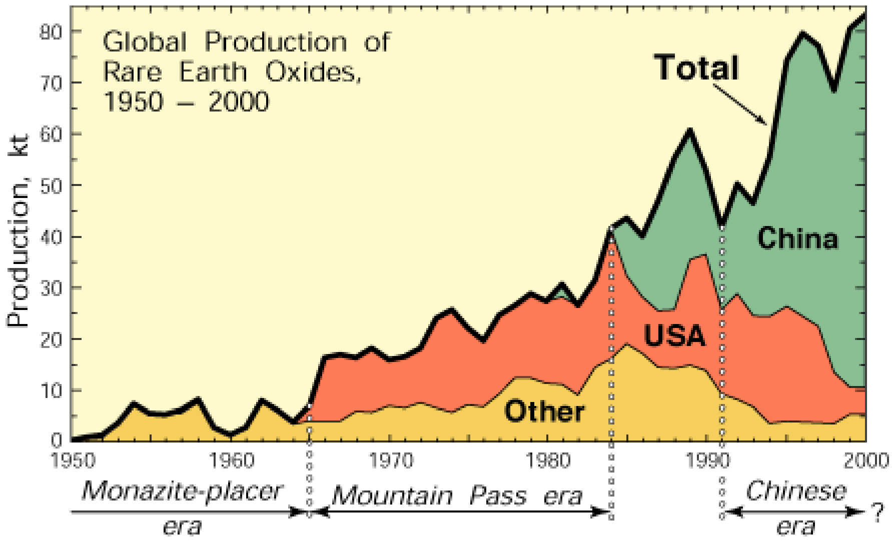


Figure 6 Historical global production of REO (source: Haxell, 2002)

The latest published numbers for world production comes from 2009, shown in figure 7. The main producer is China, followed by India, the Commonwealth of Independent States, Brazil, and Malaysia. The total production that year was 126 230 tons according to the USGS (2010).

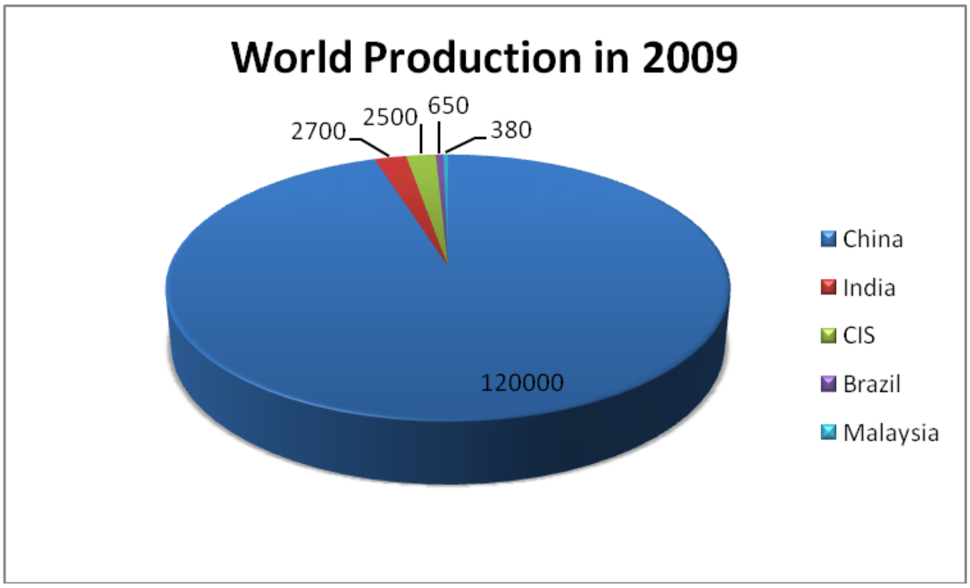


Figure 7 World production of REO in 2009 (source: USGS, 2010)

5.1.1.1 China

Even though China only has about 36% of the world's rare earth reserves, according to 2009's numbers, it has about 95% of the production (USGS, 2010). The mines are distributed in ten of the provinces: Inner Mongolia, Shandong, Sichuan, Zhejiang, Jiangxi, Hunan, Fujian, Yunnan, Guangxi, and Guandong (Buchert et al, 2011). The Bayan Obo area in the north has China's largest reserves of REO, about 90 % (Baotou National Rare Earth Hi-Tech Industrial Development Zone, n/d). The rare earth minerals in this area are monazite and bastnäsite (Buchert et al., 2011), which is rich in light rare earth elements (see table in appendix). Sichuan and Shandong also produces mostly LREE from bastnäsite (USGS, 2010). The reserves in the seven provinces in the south are found in ion adsorption deposits; these are especially rich in the less common heavy rare earth elements (BSG, 2010). According to Vulcan (2008), the ion adsorption clays of southern China contains about 80% of the world reserves of HREE.

The province Inner Mongolia in the north of China includes the Baotou city area, which is a highly industrialized area where most of the world's rare earth metals are mined. Rare earths are not the main product here, but mainly produced as a by-product to other minerals such as iron, niobium, gold, magnesium, copper and coal. The foundation of the Baotou industry is iron and steel, but the key industry is rare earths (Baotou-China, n/d). The largest company is Baoutou Steel Rare-Earth Hi-Tech Co. Ltd. (Shen, 2011); in excess of their main product, steel, the company also produces rare earth metals. Exactly how many mining companies there are in total in this area is difficult to say, and with new regulations and policies in China that will come into force 2011 the industry might change, according to plans the number of producers will decrease.

In the south of China there are many companies of different sizes in the above mentioned provinces, some of the biggest are: Jianxi Copper, China Minmetals, and Chinalco, but the industry is poorly controlled and reportedly there is also a lot of illegal mining operations (Chegwidden, J. and Kingsnorth, D., n/d). In February this year (2011) the Chinese Ministry of Land and Resources announced that, in order to protect resources and the environment, the mining in the Jiangxi province will be regulated into 11 state owned mining zones, and in the Sichuan province there will be two mining zones. (MOFCOM, 2011c) The mining industry has been causing much pollution and environmental damage in China. To address this the Ministry of Environmental Protection (MEP) has set emission standards for the rare earth mining industry, these will be the first standards especially targeted at this industry, meant to solve the problems of illegal mining, waste of resources, outdated technology, pollution and soil erosion. The emission standards will go into effect in October 2011 and there will be a grace period of two years for existing companies, but the costs might be too high for smaller companies, which might have to close down or join with bigger companies. Also, in order to protect resources, the government will introduce quotas for production and export. The effect of this could be higher prices on rare earth metals from China, as the prices would then reflect the environmental costs and restricted production. (MEP, 2011) During 2010 the Chinese government set guidelines that encouraged consolidation and merger in the mining sector. The guidelines are said to aim at reducing the current 90 rare earth firms to 20 by 2015. Also, the licensing for mining production was stopped in 2006, and since then many producers have shut down. In a publication from MEP (2010) it is said that in Inner Mongolia there is now only 18 producers remaining from what used to be 150.

5.1.1.2 India

In India there are a couple mining companies that produce rare earth elements, e.g. the governmental undertaking Indian Rare Earths Limited that has mines in Chavara, Manavalakurichi, Oscom and Aluva (www.irel.gov.in), and the Kerala Minerals and Metals Ltd. that extracts monazite from mineral rich beach sands. However, the reliance on India as a producer of rare earth metals is uncertain. According to an article in Wall Street Journal (Roy, 2010) India lacks technology to process the ore into metals, but according to the national Indian newspaper The Hindu (Dikshit, 2011) India is considering to start export rare earth chloride to the Japanese company Toyota Tsusho instead of processing it themselves, which would keep them in business. India is the world's second largest producer of rare earths, but has only 3% of the world total reserves. (USGS, 2010)

5.1.1.3 Commonwealth of Independent States

The current production of rare earth elements is located in the Lovozero district in Russia (USGS, 2010). The mineral containing the rare earths is Loparite. The Loparite ore is cracked in Solikamsk, the rare earth carbonate is then shipped to the Silmet plant in Estonia for separation (Serova, 2011). Silmet converts the carbonate into oxides, chlorides, alloys or metals (Vereschagin, YU.A. et al., 2006). The CEO at Silmet, David O'Brock, confirms that they “produce pure elements for the companies who make [electric vehicle permanent magnet and NiMH battery] components” (Serove, 2011). However, Silmet also buys rare earth raw materials from “elsewhere”, which indicates that the CIS production is not enough.

5.1.1.4 Brazil

There is no current production of rare earths in Brazil (Cilene, 2011). Indústrias Nucleares do Brasil's main business is to produce uranium fuel for nuclear plants, but they also used to produce iron titanate, titanium oxide, zircon silicate and rare earth products from mineral sands (INB, 2011). Now INB are exporting monazite to China (Cilene, 2011). The only mine in production is Buena in Rio de Janeiro with a modest annual production of 650 metric tons of REO (USGS, 2010). According to USGS (2010) data from 2009 Brazil would only have 0,05% of the world reserves of total rare earth metals. Chen (2011) however, notes that this might be a vast underestimation, as data for 2010 suggest that Brazil might actually have the largest reserves in the world. Of course, the size also depends on how reserves are defined. USGS defines reserves as the part of the reserve base that could be economically mined or produced with existing technology.

5.1.1.5 Malaysia

The REO reserves in Malaysia is an estimated 30 000 tons, they consist in the light rare earth mineral monazite, and xenotime that contains more of the heavy rare earth elements like yttrium. Both these minerals contain some radioactive elements (see chapter 3.2). The rare earth minerals mined in Malaysia are mainly byproducts from tin production. There used to be two processing plants in Malaysia: Asian Rare Earth (ARE) and MAREC. ARE was established by a joint venture between Mitsubishi Chemical Industries and BEH Minerals. The rare earth containing minerals were processed into a concentrate of about 50%, which was then shipped to Japan for further purification. MAREC produced yttrium oxide from xenotime. However, both these plants were shut down because of problems with the radioactive waste from the production. The clean-up is still ongoing. (Latifah, 2002)

A new processing plant is currently being built by the Australian rare earth company Lynas Corp., production is supposed to start in the second half of 2011. This plant will process the rare earth concentrate from the Lynas’ Mount Weld rare earth mine in Australia. Taken history into account the Malaysian government now puts strict regulations for the plant, to avoid radiation problems in the future. Lynas counteracts by saying that the new plant uses advanced, safe, modern technology, and also that the rare earth minerals at Mount Weld contains much less radioactivity than those from Malaysia. (AP, 2011)

5.1.1.6 USA

The world's third largest REO reserves are found in the United States. Historically the US used to be the dominant supplier of REE. The country's largest deposit is the Mountain Pass, where mining started in 1952. The peak production, 20 000 metric tons, was in 1990. Soon after, in 1992, the mine was closed for reasons e.g. environmental problems and competition from China. (USGS, 2010) Currently there is no mining in the US, but some processing of stockpiled ore from the mine has occurred since then. There are several projects for mining rare earths in the US, in chapters 5.1.2 and 5.1.3 two of these will be described more closely with planned output and time lines.

5.1.1.7 Australia

Rare earth production started in Australia in the late 1940s where the source was mostly beach sand (Gupta & Krishnamurthy, 2005). There are significantly large rare earth deposits with high concentration of minerals. According to BGS (2010) the Mount Weld deposit has a resource of 12.24 million tons with a concentration of 9.7% REO, which can be compared to Bayan Obo's concentration of 6%. Alkane Resources Ltd. (2009), owner of the Dubbo deposit, also reports that there are high concentrations of the less common heavy rare earth elements. There are a couple of far come projects in Australia, with planned production within the next few years, more about this in the next part of this chapter.

5.1.2 Mining expected within 3 years

This chapter will introduce some of the most developed projects for new rare earth oxide mines. The projects will be presented with planned production capacity, timeline for production start, and owner. Most information is taken from the respective company's webpage.

With increasing demand and prices for rare earth metals there are several projects exploring new RE deposits with feasible mining. The projects are spread over the world, including at least four continents. A few projects have already come a long way and are expected to start production within the next three years. These projects are listed in table 3 with some comments in the following text.

Name	Country	Company	Earliest production	Production plan (t/y)
Mount Weld	Australia	Lynas	2011	11.000-22.000
Dubbo	Australia	Alkane Resources	2013	2.600
Nolans	Australia	Arafura Resources	2013	20.000
Mountain Pass	USA	Molycorp Mining	2012	20.000
Orissa	India	Toyota Tsusho + India Rare Earth	2011	3.000-4.000
Dong Pao	Vietnam	Toyota Tsusho + Sojitz + Vietnamese Government	2012	2.000-3.000
Steenkampskraal	South Africa	Great Western Mineral Group	2013	2.700
Total Production				**75.000 (rounded up)**

Table 3 Mining projects with expected production within 3 years

5.1.2.1 Australia

Australia has a few interesting projects with far come plans. The one closest to production is Mount Weld, owned by Lynas Corporation, with an expected start in 2011. Lynas claims to have the richest source of rare earth element oxides in the world, the mineral is monazite with mostly LREE (see appendix). The production is planned to start in two phases: in the first phase the amount will be

11 000 TREO, and in the second phase it will be twice as much. The ore from Mount Weld will firstly be processed in a concentration plant 1.5 km from the mine. Here a concentrate of 40% REO will be the product from four times as much ore, which will thereafter be shipped to Malaysia for separation into individual metals in a processing plant. The processing plant, Lynas Advanced Materials Plant, in Malaysia is planned to receive its first feed in the third quarter of 2011. (Lynas Corporation, 2011)

The Dubbo Zirconia Project outside of New Wales, Australia, is held by Australian Zirconia Ltd., a subsidiary wholly owned by Alkane Resources Ltd. This project started to explore the Toongi intrusive in 2000, which contains several elements: zirconium, niobium, tantalum, and rare earth elements. The timeline is to start production during 2012. Initially the production plan is to mine 400 000 tons of ore annually, which equals about 2600 tons of REO. The production could increase with increased market demands and prices. With the initial yearly production rate the mine could have a life of 200 years or more according to Alkane (2009), however that might not hold for all the different elements in the deposit. Compared to many other deposits, Dubbo has a large share of heavy rare earth elements, about 23% of TREO. However, there is no data published on individual elements. (Alkane Resources Ltd., 2009)

A third project in Australia that has come far in planning is the Nolans Project, owned by Arafura Resources Ltd. Nolans Bore is a deposit of not only rare earths, but also phosphoric acid, gypsum and uranium. In comparison, Nolans is richer in neodymium than many other deposits (see appendix). The life time of the mine is expected to be at least 20 years with a yearly production of 20 000 tons of REO. Close to the mine Arafura plans to build a processing plant, where the concentrate from the mine will be recovered into oxides. But as the project still has not got the needed environmental approvals for construction, production is estimated to be possible in 2013. (Arafura Resources Ltd, n/d)

5.1.2.2 USA

The Mountain Pass is an old, shut down mine that used to be in production in the second part of the 20th century. This rare earth deposit was discovered in 1949, and in 1952 the Molybdenum Corporation of America (now Molycorp) started to mine its minerals and process them in small scale. (USGS, 2010) The production increased in the 1960’s; between 1965 and 1995 the Mountain Pass mine was the largest supplier of rare earth elements in the world (Castor 2008). The mine had its peak years around 1990 when the production was in the scale of 22 000 tons of rare earth oxides per year (USGS, 2010). However, as China started their production in the 1980’s competition became difficult to manage, and the sales from Mountain Pass started to decline. The mine was closed in 2002 (not only because of competition from China, but also because of environmental problems), since then there have been shipments with materials from its stockpiles to e.g. Japan. (Castor, 2008) With the rising demand and prices of REE and the restricted Chinese export, Molycorp has decided to start production again. The environmental problems are said to have been solved and production is expected to start in 2012 and amount to 20 000 tons annually. (Molycorp Minerals, 2009) The rare earth elements will be processed into oxides in an on-site facility, and also in 2011 Molycorp acquired the Silmet Plant in Estonia (mentioned in 5.1.1.3) to increase production. The acquisition of Silmet was also a strategic move in order to get manufacturing abilities and intellectual capital for a planned future production of metals. Indeed, Molycorp’s intentions are ambitious; they also have a mine-to-magnet plan (to produce neodymium magnets that could be used in EV motors) which includes the acquisition of Santoku America (an NdFeB alloy producer), and a joint venture with Hitachi (because they have the license for magnet production, more about this in 5.3). (Molycorp, 2010)

5.1.2.3 India and Vietnam

Toyota Tsusho plans to start producing rare earth elements in cooperation with India Rare Earths Ltd., who has extracted uranium and thorium from monazite minerals. A byproduct from the extraction process is rare earth chloride mixtures, which will be used as raw materials for REE production. The construction of a manufacturing plant was planned to start in 2011, and also production in the same year. The expected yearly production is 3000-4000 tons. Toyota Tsusho has also entered an agreement with the Vietnamese government to explore the possibilities for rare earth mining in Dong Pao, Vietnam. (Toyota Tsusho Corp.) Detailed information about this project was difficult to gather, which is why the source for the information in the table above comes from Roskill (Chegwidden, J. and Kingsnorth, D., n/d) instead of the company.

5.1.2.4 South Africa

The monazite mine Steenkampskraal in South Africa is mostly owned by the Canadian company Great Western Minerals Group (GWMG), who has a supply agreement on 100% of the rare earth supply of the mine. Steenkampskraal is an abandoned mine with high concentration of REO. However, the annual production plan is quite low, only 2 600 tons. Since the recoverable resource is estimated to 30 000 tons of TREO, this would give an expected lifetime of just about ten years. In this case the rare earths would be the primary product, but thorium will be stored for possible future requirements. (GWMG, 2011a) The project is currently somewhere in between pre-feasibility study and bankable feasibility study. In a press release from February 24 2011 GMWG (2011b) are still discussing different alternatives for where to separate the ore into individual element oxides, one alternative in to construct a separation plant on site. GWMG cooperates with British company Less Common Metals Ltd, who produces rare earth alloys, with a mine to market strategy.

5.1.3 Mining possible in longer term

The projects in 5.1.2 are all close to possible start-up, but there are an estimated 200 projects with a longer time to production (Zhanheng, 2011b). All projects cannot be presented here, but a few, that we found the most interesting, will be listed below (table 4). Also, to keep in mind is that many projects are only in exploration phase, with a very uncertain future. The economic feasibility of a rare earth mining project often depends on if it they are being mined as a primary product or byproduct. If they are being mined as a byproduct the mine is supported economically by the primary product, but if the rare earths are the primary product the requirements on the quality and concentration of the deposit is of high importance. In 2010 the production from the ion adsorption clays of southern China was a primary product. But for the rest of the world production, rare earths were mostly a byproduct. (USGS, 2010) What this means is that rare earth mining, due to low concentration of the elements, is often dependent on another co-product in order to pay off.

Name	Country	Company	Earliest Production	Production plan (t/y)
Ulba	Kazakhstan	Sumitomo +KazAtomProm	2015	15.000
Kutessay	Kyrgyzstan	Stans Energy	Not Announced	1.230
Kvanefjeld	Greenland	Greenland Minerals & Energy	2016	Not Announced
Hoidas Lake	Canada	GWMG	Not Announced	Not Announced
Nechalacho	Canada	Avalon Rare Metals	2014	5.000-10.000
Bear Lodge	USA	Rare Elements Resources	2015	12.000
Zandkopsdrift	South Africa	Frontier Rare Earths	2015	20.000
Kangankunde	Malawi	Lynas	Not Announced	Not Announced
Taboca Pitinga	Brazil	Neo Material Technologies + Mitsubishi	Not Announced	Not Announced
Norra Kärr	Sweden	Tasman Metals	Not Announced	Not Announced

Table 4 Mining projects with possible production in longer term

5.1.3.1 Kazakhstan

Sumitomo Corporation has an agreement on joint venture with KazAtomProm to start production of rare earth elements in the existing facility in Ulba, Kazakhstan. KazAtomProm is the world's third largest uranium producer; they also produce other metals like beryllium, tantalum, and niobium. They will supply Sumitomo with excess ore from their production as raw material for RE extraction. They will also supply infrastructure. Production still has some way left to go since it is expected to start as late as 2015. (Sumitomo Corp., 2009)

5.1.3.2 Kyrgyzstan

The Canadian company Stans Energy Corporation has purchased the, since 1991 closed, Kyrgyz mine Kutessay II. They have also agreed with the current owner, Kyrgyz Chemical Metallurgical Plant, to purchase the nearby processing plant with a private railway station. This enables Stans Energy to mine, process and transport oxides for selling. According to historical information published on the company webpage, the rare earth oxide reserve in Kutessay is approximately 88 000 tons. With a yearly mining of 300 000 tons of ore and a rare earth mineral content of 0,41 % that would mean an annual production of 1230 tons of rare earths. The approximate lifetime of the mine would be 72 years. Stans Energy also publishes data of the distribution of individual rare earth metals in the minerals (see appendix). These data implies a high share of the less common heavy rare earth elements. For example dysprosium has a share of 6.47%, which is comparable to the deposits in south of China and higher than most deposits in the world (see appendix). Overall the estimation is that the ratio between LREE and HREE in Kutessay II is about 50/50, which is very high compared to other reserves. (www.stansenergy.com) Starting date is not announced.

5.1.3.3 Greenland

Greenland Minerals and Energy Ltd are planning to finish their pre-feasible study on a REO deposit in Kvanefjeld, Greenland, in 2011. The interim pre-feasibility report states that TREO production from Kvanefjeld could be 43,700 ton per year and that the life time of the mine would be 23 years. Greenland Minerals and Energy has a time line for production start in 2015/2016, environmental and social impact assessments are due in 2013. Besides the rare earth elements uranium and zinc is also present in Kvanefjeld. Greenland Minerals and Energy wants to produce uranium oxide as a co-product to the rare earth concentrate, with an annual production of 3,895 tons. This requires mining approval from the government, since there is risk involved in uranium mining and there is currently a ban for uranium mining on Greenland. Zinc is also present, but is not included in the pre-feasibility report. (Greenland Minerals and Energy Ltd, 2011)

5.1.3.4 Canada

There are several companies conducting exploration projects for rare earth mines in Canada, e.g. Great Western Minerals Group Ltd., Avalon Rare Metals Inc., Quest Rare Minerals Ltd., Matamec Explorations Inc., and Stans Energy. Many projects are still only in exploration phase, but Canada could be a promising supplier of rare earths in the future.

Great Western Minerals Group is the owner of the Hoidas Lake Rare Earth Project in Canada. The project webpage does not reveal much information or data, but it does say that the share of neodymium in the deposit is relatively large, which is why GWMG consider it a strategic investment for expected future increased demand in neodymium for permanent magnets. The challenges for GWMG in this project lie in extracting the rare earth metals from the bastnäsite and they also report some transportation issues. (GWMG, 2010) Beyond the Steenkampskraal and Hoidas Lake GWMG also have the rare earth projects Benjamin River and Douglas River in Canada, and Deep Sands in USA, but these are only in exploration phase

Avalon Rare Metals Inc. has a project at the Nechalacho deposit in Thor Lake, Canada. The project has not yet finished the bankable feasibility study and has not yet gotten all the approvals and licenses that are needed, but time line is to start construction in 2013 and start production in 2014. Initially the production of ore would be 1000 tonnes per day, which would equal 5000 tonnes of REO per year. During the fourth year the production rate is expected to double. The expected lifetime of the mine is 18 years. The rare earth elements will be the primary product, sold as oxides, and byproducts will be zirconium oxide, niobium oxide, and tantalum oxide, which are commonly found along with rare earths. (Avalon Rare Metals Inc., 2010)

5.1.3.5 USA

Beside Mountain Pass there are a few more projects in the US. The one that is perhaps the most promising on is that in Bear Lodge, owned by Rare Element Resources Ltd. The exact amount of reserves is not stated in the interim feasibility report, but in a conceptual plan the figure for annual production is 325 000 tonnes of ore. How much REO that corresponds to depends on the concentration of rare earths in the ore, the report shows an average figure of 3.62 % REO, which would then be almost 12 000 tonnes of REO per year. However this is just a conceptual figure, future reports will have to give more certain figures. The life time of the mine is expected to be 15 years beginning in 2015. Other elements found in the deposit are gold copper, uranium and thorium. (Richardson, 2010)

5.1.3.6 South Africa

Africa does not have any recorded production of rare earths today. But there are several deposits and exploration projects running. The project that seems to be closest to production is Zandkopsdrift, held by the Canadian company Frontier Rare Earth Limited. The project plans are: target scope study finished 2011, pre-feasibility study finished 2012, and bankable feasibility study also in the end of 2012. This could lead to possible production in 2015, and the announced annual production is 20 000 tons of separated REO. The mineral from Zandkopsdrift is monazite with low average levels of thorium (0.0225%) and uranium (0.0065%). The size of the deposit or the expected lifetime of the mine is not determined. Distribution of the elements is shown in the table in the appendix (Frontier Rare Earths Limited, 2011)

5.1.3.7 Malawi

In late 2010 Lynas got the approval from the Malawi government for their acquisition of Kangankunde Rare Earth Resource in Malawi. The project is in feasibility study phase. The size of the resource depends on the cutoff grade, with a cutoff grade at 3.5 % the size of the resource is 107 000 tonnes at an average grade of 4.25% REO. The thorium content is reported to be very low. Since Lynas are about to construct a processing plant in Malaysia, the ore from Kangankunde could either be fully processed in Malaysia, or it could be concentrated in Africa and then shipped to Malaysia. There are today no figures for production rate or startup date. (Lynas Corporation, 2011)

5.1.3.8 Brazil

In 2009 Neo Material Technologies ("Neo") signed an agreement with the Brazilian mining company Mineracão Taboca for the allowance to be free to investigate the possibilities of rare earth production in their Taboca Pitinga mine. The primary product from this mine is tin concentrate, byproducts are niobium and tantalum. Neo will have access to the tailings from the tin production, which are thought to have relatively high concentration of the heavy rare earths dysprosium and terbium, and other resources. The mineral in Taboca is xenotime. (Neo Material Technologies, 2009a) That same year Neo signed a memorandum of understanding with Mitsubishi Corporation to establish a "strategic partnership" for developing a rare earth supply outside China. The partnership is not limited to the Taboca mine, but will also look for other opportunities around the world to produce rare earths as byproducts. (Neo Material Technologies, 2009b)

5.1.3.9 Sweden

There is no history of rare earth mining industry in Sweden, even though this is the country where the elements were discovered. However, there are two projects exploring the possibilities of future production. One is LKAB's investigation of possible production from tailings from their mine in Malmberget. LKAB is working together with Luleå University of Technology on this. The other project is pursued by the Canadian mineral exploration company Tasman Metals Ltd in Norra Kärr in southern Sweden. The project is still in exploration phase and drillings are being made to determine feasibility of mining. There is no announced date for possible production start at this stage. (Tasman Metals, 2011)

5.1.4 Issues related to starting new mines

As prices and demand for rare earths are rising, more and more projects are started to explore new opportunities for producing them. The time from exploration to production can be many years though, and there are many steps and procedures to be handled on the way. Most nations have rules and guidelines for mining projects, e.g. the Canadian NI 43-101, the Australasian JORC Code, and the South African SAMREC Code. These guidelines usually demands feasibility studies and technical reports. The Canadian mineral exploration and development company Avalon Rare Metals Inc. (London, 2010) presents a list of 8 stages before production is possible:

1. Grassroots: 1 year
2. Target generation and drilling: 1-2 years
3. Discovery delineation: 1-2 years
4. Infill drilling: 1-2 years
5. Bulk sample and metallurgy: 1 year
6. Prefeasibility: 1-2 years
7. Permitting, marketing and feasibility: 1-2 years
8. Construction: 1-3 years

This means that a time line of around 10 years is required from finding the reserve to actual production. There are also some other difficulties in producing rare earths, the Organization for Economic Co-operation and Development (Kim and Korinek, 2010) lists a few obstacles to enter the rare earth market:

- To process the ore into concentrates, oxides or even metals require special technology, and the technology depends on the ore and needs to be specially adapted.
- There is a high capital cost to the production of rare earths, OECD estimates USD 30 000 per ton.
- There is no official trade market for rare earths; the companies must have their own costumers.
- The production knowledge is limited outside of China
- The input costs in China are very low and difficult to compete with.

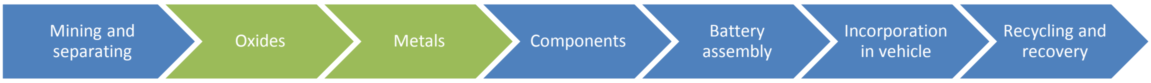
One way of handling the capital costs can be to have the rare earth production as by- or co-production with another product, such as niobium, tantalum or iron. Today there are many joint ventures and collaborations between mining enterprises, trading houses (e.g. Sojitz) and producers (e.g. Toyota). This is a way for both sellers and buyers to secure costumers/supply. The last bullet might be about to change as the Chinese government intends to put stricter regulations on the industry to protect the country's resources and environment, which could make the rare earths produced in China more expensive as the companies will have to invest in upgrading their technology (see Chapter 3.3).

5.1.5 Separation

After mining the ores have to go through separation processes in order to sort out tailings and obtain the rare earth oxides. In the initial phase of producing the rare earth metals by refining and separating oxides, approximately 25% of the ore is lost as waste and added to that is another 5% lost as slag product (Du and Graedel, 2010).

Since the majority of all production of sintered neodymium magnets are produced in Asia large parts of the world are today dependent on the imports of magnets from Asia and specifically China. The Chinese production of rare earth materials and magnets is totally dominating the global market. China produces more than 95% of the rare earth metals worldwide and is also the only exporter of commercial quantities to other countries. There are some production of rare earth metals in other countries as well, Japan for instance, but that production is not for export but for use within the country (Humphries, 2010).

5.2 Oxides and metals



As mentioned above the most of the rare earth mining occurs in China at present, the same is true for the production of the oxides, metals and alloys (Humphries, 2010). The exports of rare earth elements from China can be in the form of oxides that have to be processed further (to increase the rare earth content in the oxide), or as rare earth metals or alloys. China also has significant amounts of production of rare earth metal alloys, around 90% of global total (Humphries, 2010). This indicates that some countries buy REO and refines them into metals themselves.

During the second phase of fabrication and manufacturing, where metals and alloys are made, there are other losses in the form of scrap and industrial waste, and according to Du and Graedel the amount of losses in this phase is quite vague but an estimation of approximately 10% of material is lost in this phase.

5.3 Permanent magnets

This chapter will further explain the product chain for permanent magnets from alloys and magnet powders to components and final technologies.

5.3.1 Alloys and magnet powders

Japan is a large importer of rare earths for production of permanent magnets for the vehicle industry and Hitachi is one of the producers of such motors, especially for Toyota (Clenfield, et. al., 2010). So far Japan has mostly imported raw material, rare earth in the form of ores and intermediate raw materials, to produce their own permanent magnets instead of buying finished magnets from China. For the Japanese companies using neodymium, the raw material can be bought either in the form of pure neodymium or didymium which is a mixture of neodymium and praseodymium (Cordier and Hedrick, 2010). This indicates that countries that produce their own rare earth products import pure rare earth metals and alloys from China or produces their own metals and alloys after buying intermediate materials such as REOs from China.

5.3.2 Magnets

The production of rare earth magnets is also substantially located in Asia and mostly in China. Regarding the production of neodymium magnets, China produces 75% of the global total. Even for the production of the other type of permanent magnet, the Samarium-Cobalt magnet, China has the major part of 60% of the global total production (Humphries, 2010).

Basically, there are two different types of neodymium magnets, which most commonly have the formula $Nd_2Fe_{14}B$, sintered and bonded. The global manufacturing, sales and import of neodymium permanent magnets are today restricted by patents. The master patents are held by two groups:

Hitachi Metals and the Magnequench consortium (Hitachi, 2007 and Bauer, et al., 2010). The Hitachi group (formerly Sumitomo Special Metals), and Magnequench (formerly part of General Motors, now belonging to Neo Material Technologies), have cross-licensed each other. This means that Hitachi has the licenses to produce and sell sintered NdFeB magnets while Magnequench has similar patents for bonded NdFeB magnets (Kroll, 2011). Hitachi Group has entered license agreements with 10 companies to manufacture the Nd-Fe-B magnets and these licensed manufacturers work under Hitachi's patents (Bauer, et al., 2010). Magnequench on the other hand does not have any licensed manufacturers but only provides the metallic powder to their customers. However, when buying Magnequench's powder, the customers are allowed to work under Magnequench's patents and thereby produce and sell bonded NdFeB magnets (Kroll, 2011). Bonded magnets will not be mentioned much more in this report, but in order to understand the differences they are mentioned above. Sintered magnets have higher performance, in comparison to bonded, and are therefore mostly used in larger applications as vehicles and wind turbines. Therefore, most focus in this report will be on neodymium magnets and not samarium-cobalt magnets.

Hitachi's licensed producers are mostly located in China and around the south-western parts of Asia. There are also some production facilities in European countries, Germany and Finland. Most of the Chinese producers like Ningbo Yunsheng Co. Ltd., Thinova Co. Ltd., AT&M Co. Ltd., Beijing Jingci Magnetism Technology Co. and Beijing Zhong Ke San Huan High-Tech Co. Ltd. have their production of neodymium permanent magnets located in China (Ningbo, 2005, Thinova, 2009, AT&M, 2011, BJMT, 2005, San Huan, 2009). The Finnish company Neorem Magnets OY have some production in Ulvila, Finland, as well as in Ningbo, China (Neorem, 2009). The German companies Schramberg Magnet- und Kunststofftechnik GmbH and Vacuumschmelze GmbH have production of magnets in Schramberg and Hanau, respectively. Vacuumschmelze also have some production in Beijing, China (Schramberg, 2011 and Vacuumschmelze, 2010). For the Japanese magnets producers the scenario is somewhat different as the production facilities are more spread out over Asia. TDK Corporation has a production plant in Narita, Japan, along with two in Hong Kong, China, and one in Rojana/Wagnei in Thailand (TDK, 2011). The last company on Hitachi's list of licensed Nd-Fe-B magnet producers is Japanese ShinEtsu Chemical Co. Ltd. which have production facilities in Takefu, Japan, and also in Malaysia, Philippines and on the Indonesian island Batam (ShinEtsu, 2007). In a global perspective there has been very little or no activity in production of sintered neodymium magnets on the American continents until lately. Mostly, due to lower production costs, the production and manufacturing of sintered neodymium magnets is located in Asia except for some factories in Europe (Humphries, 2010). As seen in figure 8 below, the stars on the map indicates facilities where production of sintered neodymium magnets is located under license of Hitachi Metals. The larger stars located in China and Japan indicates that larger quantities are produced there.

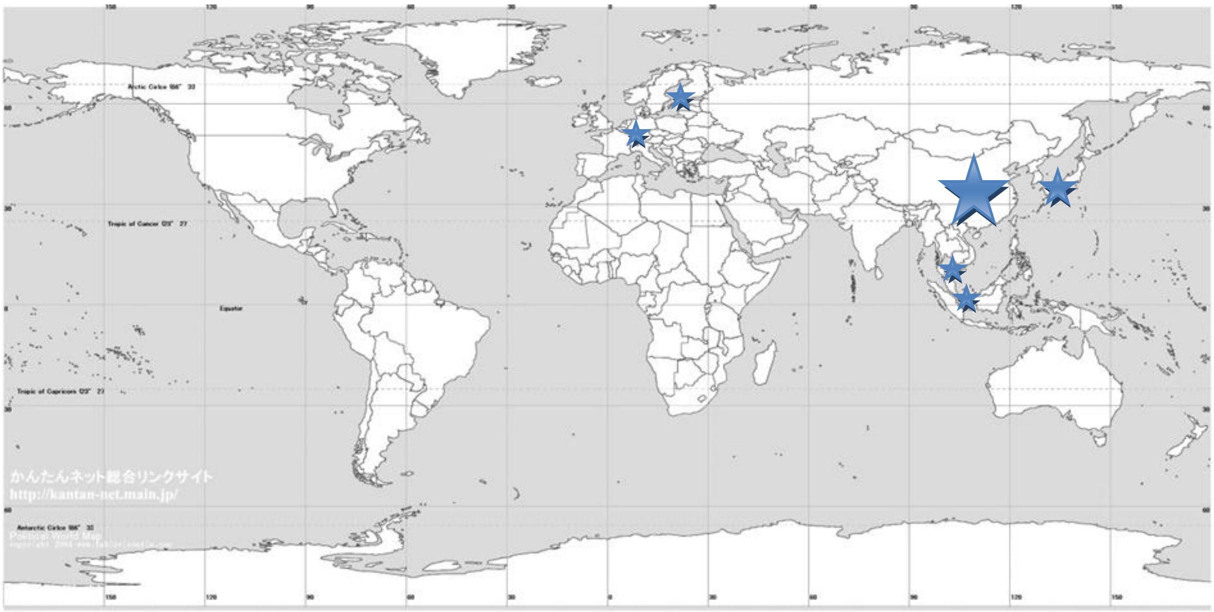


Figure 8 Global locations for production of sintered neodymium permanent magnets

The American rare earth company Molycorp Minerals has established a mine to magnet strategy for starting production of permanent magnets in the USA. For this strategy to be realizable Molycorp has acquired Estonian Silmet processing facility, and the rare earth metal/alloy producer Santoku America. Silmet was acquired in order to double Molycorp's oxide production capacity and to provide knowledge in rare earth metal production. The plan is to produce rare earth oxides, metal alloys and magnets for applications such as wind power turbines, hybrid and electric vehicles and defense system products. The permits to produce neodymium magnets are provided by Hitachi Metals. (Molycorp, 2010)

The sintered neodymium permanent magnets that are used in the automotive industry are to a large extent produced outside of China. Today China produces huge amounts of neodymium magnets, however, the net shape of the magnets does not fulfill the high standards of many certain applications and may therefore be treated before assembled into a product. This is one possible reason for Japan to produce much of their used permanent magnets themselves. The common focus for outcome of Chinas permanent magnet production is quantity and not highest quality. It is more common to produce larger blocks which have to be machined to remove extensive material. This also result in large amounts of scrap material which has to be handled (Humphries, 2010). In 2005 China produced ca 30 000 tons of sintered neodymium magnets. That same year the global production of sintered neodymium magnets outside of China totaled around 9000 tons, of which 8500 tons were produced in Japan and 450 tons in Europe (Feng, 2006).

5.3.3 Components and Final technologies

The neodymium type permanent magnet is the type most frequently used in automotive motors today since they have higher magnetic energy density than samarium-cobalt magnets as well as lower price per weight which is preferable in vehicles (Sastri, et. al., 2003). Added to the neodymium magnets are commonly other rare earths, such as praseodymium, dysprosium or terbium in order to increase the operating temperature of the magnets. This is often needed for vehicle motors that operate in higher temperatures (Bauer, et al., 2010). By using permanent magnets, space and weight is saved which is very profitable in most applications as it can reduce the price with fewer components and make products more attractive due to low weight and size.

5.4 NiMH batteries

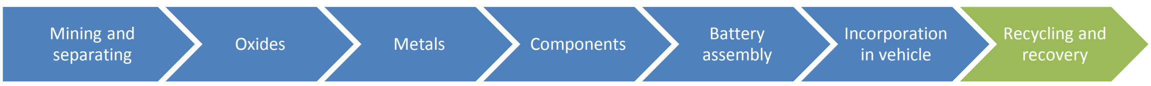
The chain of actors seems to be quite short for the NiMH batteries for hybrid vehicles. The components are made from alloys and the battery is then assembled with those components by the same battery manufacturer. There also seems to be a limited number of actors, with close relationships between battery supplier and car manufacturer. Most batteries are manufactured in Japan.

The first successful NiMH battery using rare earth metals was patented by Stanford Ovshinsky, who, together with his wife Iris, co-founded Ovonic Battery Company, a subsidiary of Energy Conversion Devices (ECD) (Zelinsky, 2010). ECD still holds the patent, but has licensed it to a number of companies. Out of these companies only a few produces batteries for use in electric or hybrid vehicles. Today Primearth EV Energy and Sanyo Electric are the largest producers, both located in Japan. Primearth, former Panasonic Electric Vehicle Energy, is a joint venture between Matsushita Electric Industrial Co., Ltd. and Toyota Motor Corporation; they produce all batteries for Toyota's vehicles. Sanyo supplies, among others Honda and Ford.

GS-Yuasa Group is a joint venture between Mitsubishi and Mitsubishi Motors, the group also includes a Honda joint venture, and Toyota is one of the principal shareholders. For hybrid and electric automotives GS-Yuasa seems to be an example of a producer that is chosing lithium-ion technology instead of NiMH: “the GS-Yuasa Group will make further efforts at (…) focus on Lithium-ion Batteries for automotives to establish it as a core for our new business” (GS-Yuasa Corporation, 2009). They report to have a planned annual production of batteries for 67 8000 electric vehicles in 2012, and in the future exceed 100 000 (LEJ, 2010). Other companies choosing Li-ion for hybrid and electric vehicles is e.g. Hitatchi, Saft, SB LiMotive and Toshiba.

The point of the part above is that there are many manufacturers that have the patent to make NiMH batteries, but two producers have become the successful suppliers for the vehicle industry. These two companies have produced more than 95% of all batteries in hybrid and electric vehicles in use today (Schreffler, 2010), and all of their production is located in Japan.

5.5 Recycling



Constant development of new technology creates a demand for new goods and products which generate huge quantities of obsolete products that will not be used anymore (Resende and Morais, 2010). There are huge quantities of waste, scrap and obsolete products which contain valuable materials and from a resource effective and economic perspective those materials can be turned into resources if handled in a proper way. Recycling of used materials is something of great concern in the development of a sustainable and growing society. In some parts of the world, at least among some different materials (paper, metals, some polymers etc.) and technological devices (mobile phones, computer monitors etc.), recycling is performed to extract valuable materials. However, most recycling is only performed if it is economically feasible without too significant losses of the materials' purity and economical value. The common saying when it comes to recycling is that what is profitable to recycle is recycled (Lehner, 2011). Regarding the rare earth elements, the recycling and after usage stages of the product chain are not very well developed. This depends greatly on the physical and technological difficulties in the processes in which different rare earth elements may be treated and recycled. The problem depends basically on two aspects, economy and technology. The alloys of rare earth elements mixed with other metals and chemicals are very complex and often contain several different compounds. This complexity makes it very difficult to use a simple process to separate the material in a sufficient way.

With the occurring situation in China with decreased exports of rare earth elements, demands for new methods of extracting rare earths are urged for. Since the rare earths usually are very stable and mixed in ores they demand large amounts of energy to obtain rare earth metals of high purity. Even if some rare earths are not that rare, they still need a lot of energy and processing, as well as there being a lot of generated waste (Takeda, et. al., 2005). Therefore, recycling could be a good alternative to provide REMs. However, the recycling of rare earth metals is not very common yet, but still there are some different methods available to extract rare earths from discarded products.

There were in the year of 2005 approximately one billion of used NiMH batteries which totally contains light rare earth metals, like lanthanum, cerium, praseodymium and neodymium, to an amount of 2500 tons (Li, et. al., 2009). To address this problem there have been many hydrometallurgical methods developed in order to extract rare earths from scrapped batteries. These methods can basically be described as chemical dissolution of the compounds of the batteries, through the processes of leaching, solvent extraction, evaporation and crystallization. In various steps the rare earths are solved and extracted by using chemicals, water and energy (Li, et. al., 2009).

Several studies have been performed where different types of acids are used as leaching agents in order to recover europium and yttrium from old color TV screens (Resende and Morais, 2010). This example along with the mentioned processes above and in chapter 4 indicated that there are possible ways to recover and recycle rare earths from different applications, and that this can be done with a high purity of the outcome.

China has the major role of what is happening in the rare earth industry today. Since China has the dominating position of production and exportation of rare earths, it also affects the market and afterlife processes of products containing rare earth elements. The increasing demand for rare earths in various products around the world along with the increasing use of such elements within China has created difficult situation where the demand for rare earths might exceed the availability. The expansive market of rare earths has in the last two decade generated a stock of rare earths bound in products. By recovering these rare earths or at least parts of it, might be a reliable source for future demands of rare earth elements (Du and Graedel, 2010).

Still, the situation is not easy since the different stages of the material flow of rare earths are not completed. Looking at a Material Flow Analysis (MFA) for these elements, the primary stages of production, fabrication and manufacturing, and the use phase is well known but the final phase, waste management and recycling is not as well developed (Du and Graedel, 2010). When looking at the flows of material within these different phases it becomes clear that a lot of material, rare earths that is, “disappear” during the material flow stages. As mentioned earlier there are losses in the separation and refining stages of the production cycle but. The third phase, use stage, is the phase where the rare earths are put into products and this is very difficult to estimate numbers of losses since rare earths often are used in alloys in various products, for instance permanent magnets that may contain neodymium, praseodymium, dysprosium, gadolinium and terbium (Du and Graedel, 2010). Most of these applications contain alloys or rare earth compounds that are very stable and/or assembled in a way where leaching or loss of material is not very likely to happen. However, in figure 9 and 10 below numbers of in-use stocks are visible, which indicates the amount or rare earth metals that might be recovered or seen as a resource when the product has served its purpose and turns into waste.

The last phase of the material flow stages is recycling which is the least covered phase. This depends mostly on economic and technical issues. The technical issues are a problem due to complexity and advanced procedures in recovering the elements and this also becomes an economical issue since energy, chemicals, equipment, technology, disposal and/or treatment of wastewater generates high costs. If the amount of recovered rare earth metal is too small, the value of the outcome cannot cover the expenses of the recovering process and thereby not being feasible (Ekberg, 2011, and Lehner, 2011). On the other hand, if the demand for rare earths increases even more, which is not unlikely, cost effective processes of recovering rare earth elements have a high potential.

According to Du and Graedel, 2010, the in-use stock of cerium, neodymium, lanthanum and praseodymium was in the year of 2007 four times the annual extraction rate for these four elements in that very same year. This is a good example that shows the amount or rare earths that are in circulation in current technology, and a possible stock that may be able for recovery and recycling. In figures 9 and 10 below, the in-use stock use by the year of 2007 can be seen for various rare earth metals in different applications. A possible increase of recovery and recycling or rare earth metals could result in a decrease of mining for virgin material which is today is the most common source for rare earth elements (Du and Graedel, 2010). To make recycling of rare earth elements sufficient and economically feasible the amounts of recycled outcome has to be large enough. This makes the recycling of larger applications more likely to be the choice of possible future recycling of rare earth elements (Du and Graedel, 2010). Possible element to recycle are rare earths such as neodymium, lanthanum, cerium and praseodymium, which all are used in fairly large quantities and in large applications like for instance in automobile catalysts, permanent magnets in car engines and wind turbines. Due to the large quantities, the recycling can be performed more efficiently (Du and Graedel, 2010). Smaller applications demand for very accurate and effective recycling processes and are therefore not likely to be recycled in the nearest future (Du and Graedel, 2010).

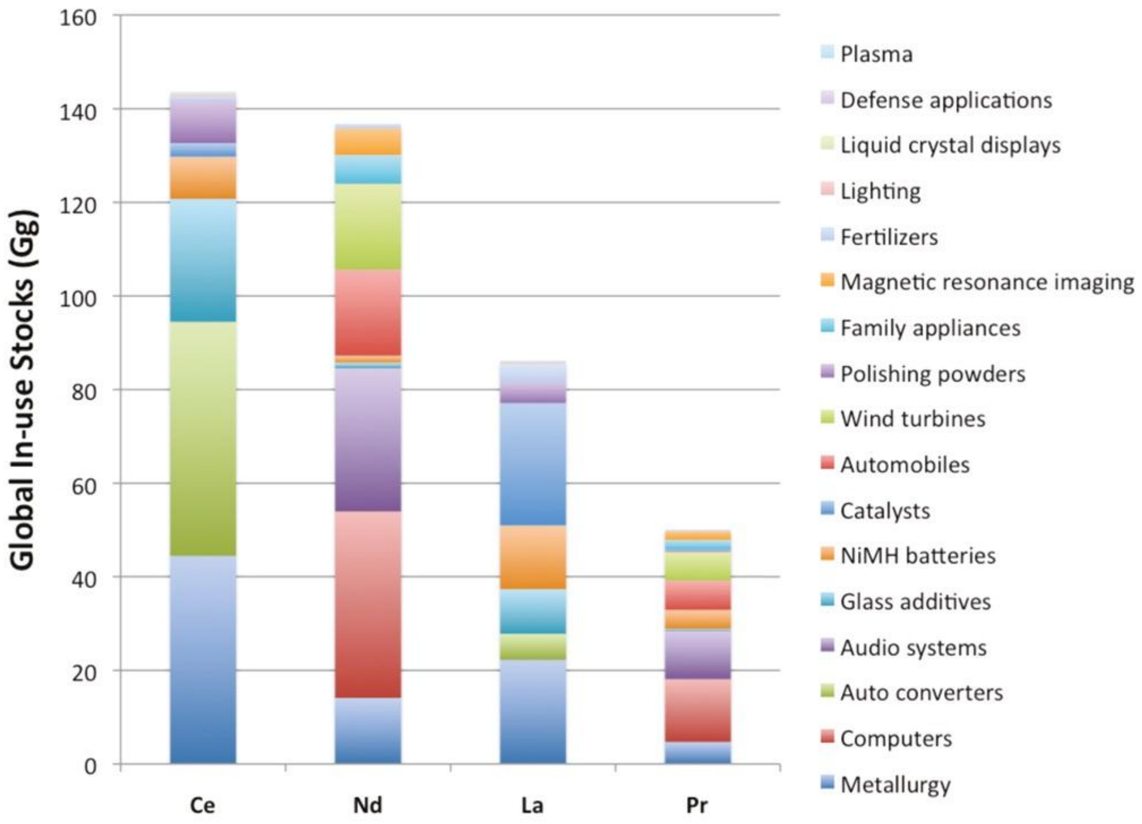


Figure 9 Global in-use stock for some of the most commonly used REs in 2007 (source: Du and Graedel, 2010)

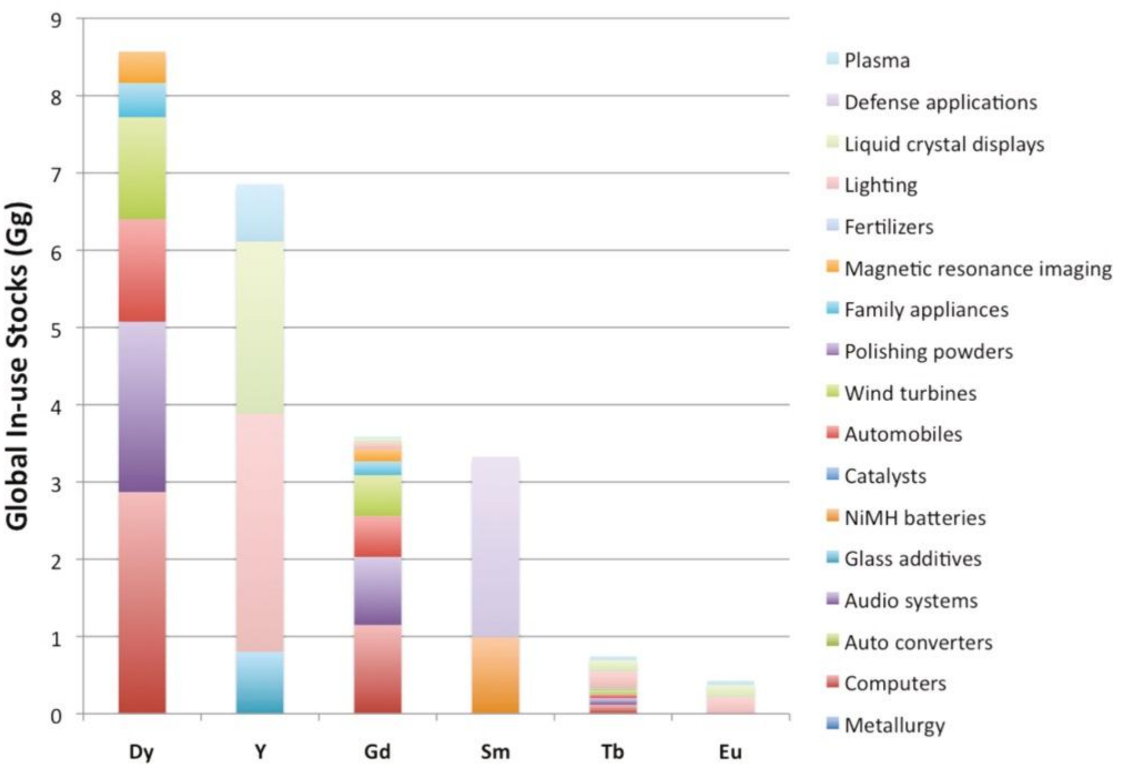


Figure 10 Global in-use stock for some of the less commonly used REs in 2007 (source: Du and Graedel, 2010)

Already there are companies that have started to look at recycling of rare earths mainly to supply for domestic use and to cover some of the own usage. One of the companies that more or less have started to recycle rare earth metals is Japan's second largest rare earth magnet producer Shin-Etsu Chemical Co. that has plans to start recycling of rare earth metals in used air conditioners and thereafter reuse the metals in permanent magnets (Nikkei, 2010 and Sadden, 2011). Shin-Etsu has the metallurgical knowledge of handling rare earths and how to extract them from ores and oxides, and this knowledge can be used to extract the rare earths from the air conditioner motors (Nikkei, 2010). From a magnet of 50-100 grams from the motors, approximately 30% can be extracted for reuse. Shin-Etsu already has a plant that extracts rare earths from their own production scrap. There are also possibilities to recycle rare earths from other applications and products like hybrid-vehicle motors etc. (Nikkei, 2010).

Stated on the Green Car Congress homepage, there is collaboration between Toyota Motor Corporation, Toyota Chemical Engineering, Sumitomo Metal Mining and Primearth EV Energy Co., Ltd. where they have come up with a process to collect and recover NiMH batteries. The process can be described as battery-to-battery recycling where used batteries are collected, dismantled, reduced, sorted, refined and finally processed into new NiMH batteries. The process chain can be seen in figure 11. There are also investigations going on by Toyota Motor Corporation to see the possibilities of using this process in America (GCC, 2010)

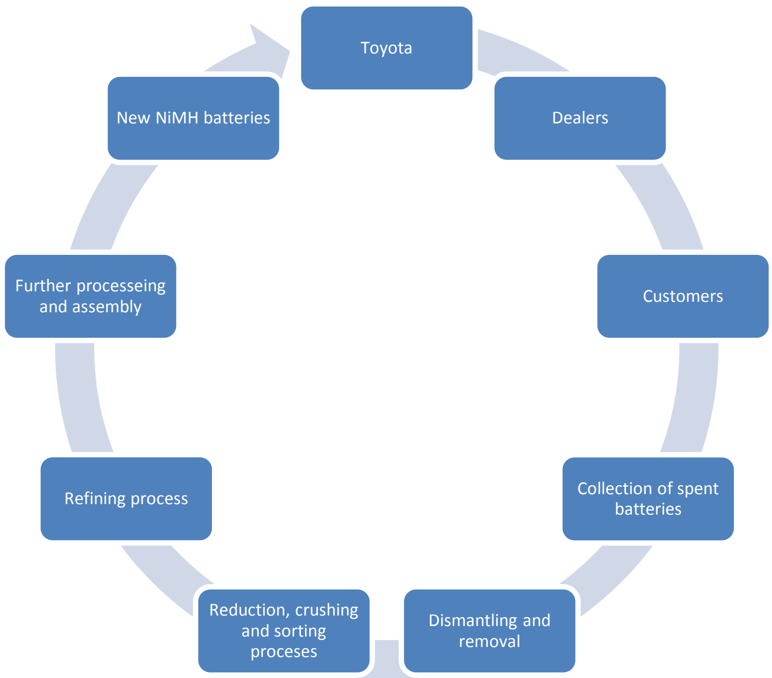


Figure 11 Description of battery recovering process for Toyota (GCC, 2010)

Another company that has started to look for recycling options is the biggest rare earth company of Japan, namely Hitachi Ltd., who produces motors for the Toyota Prius hybrid car. Hitachi uses approximately 600 tons of rare earth metals every year and is therefore dependent of a stable supply or rare earth resources (Clenfield et. al., 2010). Since China has cut the export quotas of rare earth elements, Hitachi has plans of using recycling as a resource to cover some of the company's need for rare earths. Today the recycling is more or less nothing. However, a quite realistic future perspective is that 10% of the Hitachi's need for rare earth metals shall come from recycled metals (Clenfield et.

al., 2010). Similar to Shin-Etsu's processes of recycling rare earths, Hitachi also uses spent air conditioner motors which are opened in order to recover the permanent magnets inside of it. This sudden boost of plans to recycle rare earths has settled new recycling projects in other companies as well. The Japanese chemical company Showa Denko KK has opened a plant to recycle dysprosium and didymium, a mixture of neodymium and praseodymium, in Vietnam. Also Mitsubishi Materials Corp. along with Panasonic Corp. and Sharp Corp. has projects going on to investigate the costs of recovering neodymium and dysprosium from products like washing machines and air conditioners (Clenfield et. al., 2010 and Sadden, 2011).

Increasing of conventional and green technology increases needs of REMs and therefore recycling is needed can be seen as a good alternative supply. So far the recycling has been held back, mostly due to economic and technical issues, where the technical issues greatly affect the economic issues due to, efficiency, expensive equipment and technology, energy and waste treatment (Ekberg, 2011, Lehner, 2011 and Weihed, 2011).

There are also other projects going on worldwide where other sources are investigated for future supply of rare earth elements. An example of such projects is recovering of rare earth metals from tailings of old mines. For instance in northern Sweden, LKAB (Luossavaara-Kiirunavaara Aktiebolag) has started a project along with Luleå University of Technology (LTU) where they look at the possibilities of extracting and recovering rare earth metals from apatite (Lehner, 2011).

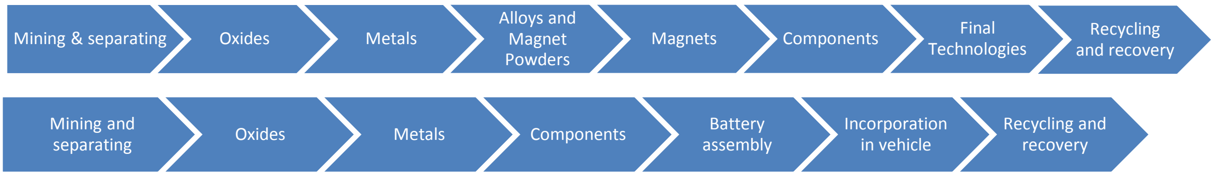
Tests of the apatite in Kiruna and in Vitåfors, Malmberget show that it contains 15 different rare earth metals, which if mined have the possibility of gaining production values in the magnitude of billion Swedish crowns (kronor). Right now, LKAB has collaboration with LTU in order to test different methods for extraction of these rare earth metals (Magnusson, 2011). If the project will result in production of rare earth metals this might be realized in the year of 2015. As of today the rare earth metals in the apatite is treated as impurities. According to LKAB a yearly production of 400000 tons of apatite would be possible during a period of 14 years. The apatite contains rare earth metals to an extent of 0,5 % which during the time period would result in approximately 28000 tons (Magnusson, 2011). The rare earth metals that exist in highest amounts in Kiruna are yttrium, cerium, europium, terbium and neodymium (Magnusson, 2011).

According to this example in Kiruna there are possibilities to start extracting rare earth metals from many different resources than regular virgin mining. Today and in the future alternatives like above mentioned recovery from spent products and scrap metals, extraction from mined tailings like apatite and effective recycling might be available in an economic and technically available manner.

According to Toyota, 2010, the company had by October 2010 produced more than two million Prius hybrid cars. Each Prius car contains approximately 1200-1500 grams of neodymium, 5400 grams of lanthanum, approximately 1900 grams of praseodymium and 900 grams of Cerium. This means that those two million produced Prius hybrids by the year of 2010 contain approximately 2400-3000 tons of neodymium, 10800 tons of lanthanum, 3800 tons of praseodymium and 1800 tons of cerium. Sooner or later the lifetime of these two million Priuses will come to an end which if recycled could generate a significant amount of recoverable rare earth metals. These two million hybrid vehicles alone could generate thousands of tons of rare earth metals if recycled efficiently.

6 Speculations about a possible product chain in Sweden

This chapter will discuss the possibilities of having parts of or the complete product chain for production of permanent magnets and NiMH batteries, containing rare earth elements, in Sweden. The text will be speculative in its nature and include features of discussion since it is talking about the possibility of a future scenario.



Sweden is a country with a well-developed metallurgical industry. For instance companies such as LKAB, Höganäs AB and Boliden AB possess knowledge within the metallurgical science and Sweden as a country is also well developed from a recycling point of view. The future possible Swedish participation of the rare earth product chain depend much on how far the mining companies want to go in the purification of metals and if the rare earth elements could be processed under economically feasible circumstances (Weihed, 2011). If Sweden has highly effective processes it could be used for competition with developing countries (Weihed, 2011).

6.1 Mining and Separation

Sweden has a long history of producing different types of metals, such as iron, copper, silver and gold. The knowledge and efficiency within the processes is well developed and even with high salaries compared to less developed countries it is possible to mine and separate metals profitable from an economic point of view (Weihed, 2011). Since Sweden has known sources of rare earth elements at various locations in Sweden it would be technically possible to mine those sources for rare earths. This can be done from virgin mining in Norra Kärr if that project will be realized. Other solutions than virgin mining is as mentioned in earlier chapter 5.5 for instance extraction from apatite from the mines around Kiruna. From an economic point of view the availability and percentage of rare earths in the ore are of great significance when considering realization of mining in Sweden. If the content in the ores is high enough it could be mined and separated. The knowledge from mining and separation among other metals in Sweden adds to the advantage of how to handle metals and what processes to use for separation. (Tengzelius, 2011 and Weihed, 2011)

6.2 Oxides and metals

The stages of refining the separated ores further into oxides and metals could also possibly take place within the Swedish borders. Again the knowledge within refining other metals would help to provide the know-how in order to process the separated ores into oxides and later metals. The processing of ores in order to produce rare earth oxides and metals demand wet processing with acids and chemicals which creates large costs especially from an environmental perspective and laws for handling of toxic chemicals, water and waste after the processes. However, if the regulations and laws regarding such issues were the same globally, the costs would not be that varying across the world depending on location and/or lack of environmental laws, as it is today (Tengzelius).

6.3 Alloys and Magnet Powders

The powders and alloys could be produced in Sweden under the right circumstances. Höganäs already has significant knowledge in producing ferrous powders and such metallurgical knowledge could be very useful also in the production of rare earth alloys and magnet powders. As of today Höganäs is producing ferrous powders competitively in comparison with China. This depends much on the high level of automation within the production stages. If the processes could be performed with a high level of automation the production of rare earth metals could be possible as long as the level of material is sufficient and not too difficult to enrich. With a high level of automation the limiting factors turns out to be energy and raw material. Tengzelius at Höganäs estimated a possible annual production of rare earth metals in Sweden to the magnitude of 20 000 tons in order to be economically feasible, but this number is still very uncertain and may vary due to uncertainties in costs, processes, wages, availability etc.

6.4 Magnets, components and final technologies

This part of the product chain is more uncertain since Sweden today does not have that many industries that use rare earth magnets, except for maybe some electronic companies, possibly among car manufacturers and wind power companies. The Swedish interest in the final stages of the REE product chain depends quite much on how the development within Swedish industry will be the coming years. Sweden has two semi-large car manufacturers: Volvo and SAAB, which might provide some potential market interest in hybrid vehicles and therefore permanent magnets and NiMH batteries. Possibly there could be an interest in producing rare earth metals and alloys for production of batteries and permanent magnets in case of a growing market and demand for such products within the industry. The market for wind turbines and hybrid vehicles seems to grow but if it is economically feasible to produce permanent magnets and NiMH batteries is very hard to tell since these processes are very well established in Asia and the competition is tough.

6.5 Recycling

The recycling situation in Sweden today is quite well developed and many different products and materials are being recycled; from light bulbs, batteries and refrigerators to materials such as iron, copper, glass and cardboard. Today car engines are recycled in separated processes for steel and copper. Often the whole engine is grinded to powder and then the steel and copper is separated in order to recycle them individually (Tengzelius).

7 Analysis and discussion

This chapter will both analyze and discuss the results from chapters 3, 4 and 5. In this chapter we will allow ourselves to discuss from our own perspective, which we have gotten after studying the topic for almost six months.

7.1 Mining

At present there seems to be a rare earth race going on in the world, with more than 200 exploration projects for rare earth mining. Rare earth production could turn out to be a lucrative business if demand continues to rise. Increasing prices for REO makes them an interesting investment opportunity and mining projects will have a better chance for financing. Also, for companies like Toyota and Sojitz it is an urgent matter to find ways to secure supply in the future, which has lead them to invest in mines of their own. China's dominance in the market is about to meet challenge, as new mining projects has started on almost every continent of the world. This gives the impression that we need not worry about the supply of rare earths in the future. And that might be correct. But, there are a few things to keep in mind; firstly, most of these projects are still in exploration phase. This means that they are not yet feasible for mining, and even if they will be, it takes years to come into production considering all the obstacles and bureaucracy associated with rare earth production (see chapter 5.1.4). So the question is if the new production will start in time, before there might be a supply shortage. Secondly, the demand is not the same for all rare earths and they do not occur in the same percentages in the REO, so even if the total REO produced will meet the predicted demand there could still be deficits for some of the elements (as well as excess of others).

China is today trying to consolidate its industry, mitigate environmental destruction and illegal mining operation by closing down smaller mines, cutting export quotas, introducing stricter regulations and higher taxes. In the heated debate it is sometimes implied that China came to dominate the RE production with unfair means of competition, such as lax regulations and low production costs. This might be quite true, that they did have less regulation (that was not enforced) and lower costs. But the money from REs has come with a price, that of destroyed environment and human health. From a Chinese perspective one could wonder if the world RE dominance has been worth it. Up until recently, there has been many RE miners in China which means high competition, and lax regulations which means low control. And since there is no official trade for REs it has been a buyers' market in which the price has not reflected true costs (if including e.g. environment and health).

When listening to the debate on China's export of REs it is very difficult not to become biased, it is sort of China against the rest of the world. And the rest of the world speaks more often and louder. Some are implicating that China is using their RE resources to exert control and power, that they got the dominance on the market because they could sell low cost REO and now when the rest of the world is dependent they cut exports. Another event that could strengthen the opinion that China is keen on keeping the RE dominance is that the Chinese government tried to buy the Mount Weld mine in Australia, but the Australian government said no. However, if China comes through with the stricter regulations, consolidations, policies, taxes and production quotas it could protect their environment and resources as well as setting a fair price that other non-Chinese producers could compete with. There might also be other explanations why China wants to cut exports; in chapter 3.1 we mentioned that China has plans to build 500 000 hybrid or electric vehicles between 2011 and 2015. This means that the domestic demand for rare earths in China will increase substantially. By how much, depends on which technology will be used. In the pure electric vehicles the batteries will probably be Li-ion, but in the hybrids NiMH could be used. However, permanent magnets will probably be used in all the engines, if no new technology is invented. This will mean that China will, themselves, need more of the rare earths that are most susceptible to deficit.

The political issues related to rare earths change all the time. Even though China sets stricter regulations, they are yet to be enforced. The export was to be set 35% lower in the first half of 2011, yet a recent article in Wall Street Journal (Yap, 2011) reports a 33% rise on the year for the exports in the first four months of 2011. This is one of the most important reasons why this report should not tell the reader about what will happen in the future when it comes to rare earths. The aim of this report is to give some background information and sketch a picture of the current situation, so that the reader can follow the news and him/herself work out the future.

The mines listed in 5.1.2 could together produce as much as 75 000 tons REO annually by 2014. If Mark Smith at Molycorp would be right in his anticipation of a world demand of more than 200 000 tons REO by 2015, this new production would cover the approximate 65 000 tons that would be missing compared to the 2009 production of 126 000 tons. If China's production would decrease or their domestic demand would increase to the extent that they would stop their export totally by 2015, and Zhanheng would be right in his estimations of an outside of China demand of 80 000 tons, there could be a supply shortage. There are a lot of speculations circulating in the rare earth "blogosphere" about future demands, China's actions, and mining projects. To draw any conclusions from this is like predicting the weather for a month ahead; there are large uncertainties within limits. The future predictions depend a lot on world economic situation, technological developments, and politics.

Just comparing numbers for future demand and supply of REO can be misleading since the demand for the individual elements will vary significantly depending on the technologies that uses them, and the supply will depend on where the REO is mined since the distribution of individual elements differ in different deposits and minerals. If the market for hybrids and electric vehicles, and windmills increase there might be a future shortage of neodymium, dysprosium and terbium. The latter ones are not used in large shares in these applications (compared to the other rare earths in the same applications), but they are HREEs which are rarer and usually occur only in small amounts in the REO. Neodymium is a LREE, but since there are several applications competing for it there could still be a risk of shortage. If looking at the occurrence of the individual elements in the oxide of the existing and new mines (see appendix), it turns out that China probably will play a big part in the supply of HREEs in the future as well. Important to say is that the numbers for the rare earth content in the REO in the new mines, collected in the table in appendix comes from the companies who owns the mines, which makes them less reliable than those numbers from USGS. Also, not all companies would reveal the distribution of elements in their REO, so there is much data missing in this report. One example of this is the Kvanefjeld project, owned by Greenland Minerals & Energy. They claim that the deposit has a very high share of heavy rare earths, but no exact numbers for individual elements are published.

7. 2 Permanent magnets

Rare earth metals are and most likely will be a very important piece of the foundation of future technology and green development of the industry. The increasing sales of hybrid vehicles and wind power plants will increase the demand for permanent magnets since that is the best technology serving these purposes so far.

As of today the market for hybrid vehicles and wind power plants seem to be increasing and the production of the Toyota Prius has increased almost every year since it first was put in production. As shown in table 5 below, the Toyota hybrid vehicle Prius has increased its sales annually every year since initial production except for the year of 2002 when sales decreased a little. This might be an indication that people find hybrid vehicles appealing and a good sustainable technology (Toyota, 2010).

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Jan-sep 2010	**Total**
Japan	0,3	17,7	15,2	12,5	11,0	6,7	17,0	59,8	43,7	48,6	58,3	73,1	208,9	254,2	**826,9**
North America	0,0	0,0	0,0	5,8	16,0	20,3	24,9	55,9	109,9	109,0	183,8	163,3	144,3	105,9	**939,1**
Europe	0,0	0,0	0,0	0,7	2,3	0,8	0,9	8,1	18,8	22,8	32,2	41,5	42,6	35,5	**206,1**
Other	0,0	0,0	0,0	0,01	0,2	0,2	0,4	1,9	2,9	5,3	7,0	7,7	8,4	5,8	**39,7**
Total	**0,3**	**17,7**	**15,2**	**19,0**	**29,5**	**28,1**	**43,2**	**125,7**	**175,2**	**185,6**	**281,3**	**285,7**	**404,2**	**401,3**	**2011,8**

Table 5 Annual sales of Toyota Prius 1997 - September 2010 (source: Toyota, 2010)

The growing markets for hybrid vehicles and wind turbines will most likely increase the production of permanent magnets since that technology is the most efficient and cost efficient alternative so far. Increasing production of permanent magnets will result in increasing demands for rare earth elements such as neodymium, dysprosium, praseodymium and terbium, which are the most important ingredients in neodymium permanent magnets. The numbers shown for the sold Prius hybrids are only for the model Prius and it might be good to consider that there are other car manufacturers than Toyota that also produces hybrid vehicles with similar technology using permanent magnets. Other car manufacturers that produce hybrid vehicles with combined combustion and electric engines are for instance Honda, Nissan and Mercedes to name a few. As long as the stocks of REMs do not become too scarce the technology of permanent magnets will probably stick around for quite some time.

The future of neodymium permanent magnets is from one point of view hard to predict. This is due to the fact that many of the patents that restrict the production of such magnets expire in the coming years. What will happen to the market then is difficult to foretell. Possibly if the patents do restrict who can produce the magnets there might be greater competition and possibly more competitors on the market. There are also possibilities of prolonging some of the patents to keep the restrictions of who can produce the Nd-Fe-B magnets. However, there is very little published information about this and what might happen within the coming years.

7.3 NiMH batteries

The NiMH battery is the most commonly used in the hybrid vehicles on the roads today. This is a lot thanks to Toyota who decided to use these in their very popular Prius. There are other kinds of batteries that can be used in hybrids, but Toyota managed to find a way to mass produce NiMH batteries cost effectively. Chapter 5.4 estimates that a modern battery used in the Prius contains about 10 kg rare earths, of which at least two (dysprosium and neodymium) are forecasted to be in deficit in the future. However, for the future of hybrids and plug-in electric vehicles this does not have to present a problem. The reason is that many battery manufacturers are producing and/or developing Li-ion batteries instead. Even Toyota will be using Li-ion batteries in a coming plug-in version of Prius.

Studying battery manufacturers show that many companies has the patent from Ovonics to produce the NiMH battery, and many has also put research into developing a battery for vehicles. However, most companies do not seem to have been successful, many are now switching to Li-ion instead. The companies that have succeeded have been those with a close partnership with a car manufacturer, e.g. Primearth (former Panasonic) and Sanyo. A guess is that this partly has to do with the cost effectiveness of mass production, made possible with reliable demand.

The question is then if the NiMH battery is an obsolete technology. Our answer is: maybe. The NiMH will probably stay on the market for years to come, since it is an established technology that is successful. But for the future the Li-ion battery will probably be a preferred alternative. For plug-ins it is definitely the preferred choice since its qualities are better suited for that application. But depending on how the price curve for rare earths will develop in the future, Li-ion could perhaps also be the more cost effective choice. The conclusion is that the NiMH battery using rare earths do not seem to be a restricting factor for the growth of the hybrid or plug-in car technology.

7.4 Recycling

The demand for rare earths might also increase the possibilities of recovering rare earths from scrap metal and discarded products. As indicated in chapter 5 there are huge quantities of rare earth metals in use that at some point will reach the end of their lifecycle. This opens up for recycling instead of mining for virgin materials. In a future perspective it is likely that the mining of virgin rare earth elements will increase as well as recycling and recovering processes probably will be further developed and put into use. The material recycling and recovery from scrap and discarded products might be a very valuable asset for countries without much natural resources, like Japan, who has an extensive industry and a need for raw materials. It would also make such resource poor countries less dependent on imports from other countries.

According to articles and other published documents there seems to be quite a lot of activity in the area of recycling of rare earths currently. There has been a boost of interest in recycling processes that might be a result of the decreased exports quotas of REMs from China and rising prices. The demand for secure deliveries of REMs and stable stocks pushes the development of recycling methods that could recover large amounts of REMs in an efficient and economically feasible way.

Products that at some point in the “end-of-life” stage could be recycled or recovered could be permanent magnets in wind turbines, motors, catalysts, air conditioners, computer monitors and other larger products. When it comes to hybrid vehicles, the ones produced by non-Toyota manufacturers added to the two million sold Prius cars till September of 2010 can be seen as a valuable stock of potential recyclable and recoverable resource since there are REMs in the motor and the batteries. Worth noting is that there is only about one kilogram of rare earth elements in a hybrid vehicle motor and around ten kilograms in the battery while there might be several hundred kilograms in a wind power plant which could be an even more important asset of valuable rare earth elements in the future. Most likely the recycling and recovering of REMs will in the initial stages only handle larger applications that contain fairly large amounts of REMs. Too small contents of REMs are in the initial phase not going to be economically feasible to recover. There will probably be a lot of development in the area of rare earth recycling and recovering in the coming years.

7.5 Sweden perspective

There are both possibilities and disadvantages of having parts of the rare earth product chain in Sweden, but worth mentioning is that it is very hard to estimate the likelihood and to what extent Sweden can take part of the product chain. Still, it is an interesting topic to speculate about. The greatest disadvantage from a Swedish perspective might be if there is a need for very large investments to small resources, and this insecurity might be a long term problem as investors prefer security. Many different perspectives can be taken into consideration when assessing the probability of having parts of the production chain in Sweden. It very much depends on economic and technical issues. Considering the Swedish knowledge within metallurgical processes it would be likely to obtain the know how in order to process REMs. The main issue would in that case be the economic aspect. It is difficult to estimate how much of an issue this might be but since Sweden does not have any parts of the product chain today it would most likely demand large investments in order to obtain processes in Sweden. Contributing factors that might affect the outcome would be the possible benefits for Swedish industry, possibility of exports, demand and market request. In an initial phase the mining for virgin materials or recovering of REMs from tailings would be possible activities since these are being evaluated and researched right now. Regarding the refining processes of REMs it is more difficult to estimate the Swedish participation. The part of the product chain that is closest to realization is probably virgin mining, possibly in Norra Kärr, or perhaps extraction of rare earths from apatite deposits.

It would have been interesting to discuss this topic with more people within the metallurgical industry in Sweden but it is also difficult to find people with knowledge about an industry that does not yet exist in Sweden. A contributing factor that also is an obstacle for the possibilities of producing rare earth permanent magnets in Sweden is the restricting patent laws. If the restrictions are dismissed or permissions granted it would be legal to produce neodymium permanent magnets in Sweden. However, the feasibility of producing the magnets in Sweden could be questioned due to labor costs that might be higher in Sweden than in Asia. From this perspective the level of automation in the production stages also becomes very important. With more automatized processes the cost for employees decreases and makes it easier to compete with low wage countries. Also the efficiency of the processes becomes an important factor. Highly efficient processes could add to the benefits as high efficiency increases the output of material in comparison to the input which result in less waste and scrapped material. Under right circumstances and with a market for rare earths in Sweden and Europe the likelihood of having parts of the production stages of rare earth permanent magnets is a possibility. Sweden has great knowledge within metallurgical industry as well as knowledge about highly technological processes which speaks for the rare earth industry taking place in Sweden.

7.6 Method

When the work on this report first started there was a reasonably clear idea of what it was supposed to contain and what the outcome was going to be. The tools that were used in this report we were already acquainted with from earlier in the master program Industrial Ecology here at Chalmers. Therefore they were sort of conjointly used instinctively from the beginning without there being a defined method yet. This meant that we had to sort out which tools we were using, how and in what stage of the work.

The perspective on the product chain was taken from LCA, where the whole life cycle with all its processes are included. There was however no interest in performing the impact assessment of the LCA, this tool was just used as a way of thinking about the life cycle of the rare earth elements. Chapter 3 briefly mentions some of the environmental impacts from the mining, since this is of course an important matter when considering sustainability of rare earth production, but this is just to inform the reader about the issue. It would have been interesting to look more closely at this, especially since rare earths are used in “green” technologies. Perhaps to compare impacts from the production of the rare earth raw material, and the impacts the products containing rare earths would save (compared to other products with the same functions, e.g. 100 km driven with a Prius versus gasoline combustion engine car). However, this was not the purpose or aim for this report.

The perhaps most influencing tool was the MFA. The flow of material in the product chain has been mapped on a global scale to the extent possible. The interest was to see where this raw material was produced and where it goes from there. The thought behind this was to prepare for the TA, where one of the research questions was if rare earths will be a constraining material in the future because of insufficient supply. The exact quantities for the flows have not been balanced, that would have been very difficult to do because it would have been difficult to find data for it for several reasons. One of the reasons is that this report was limited to six elements that are used in specified applications, but rare earth elements are often sold as oxides (in which they are mixed). Therefore it is difficult to find out which flows will end up in hybrid vehicles. Some numbers that are relevant for discussing the research questions have been presented: reserves, production, in-use stocks, and demand.

The parts of the MFA that were excluded were replaced with CCA. Instead of tracking the exact flow quantities, the actors using the material were mapped. In some stages there were many actors, more than could be individually listed, in those cases they have been dealt with as a group with common features. One example of this is all the miners in China; they have been dealt with as a group since they are all found in the same nation, producing the same raw material. In later steps it was easier to distinct different actors, e.g. the actors that had licenses to produce sintered permanent magnets. Inspired by CCA the report has also tried to distinguish the relations between the actors in the chain; where in the chain can e.g. joint ventures be found and why. The reason for this is that when it comes to rare earth elements the numbers for reserves and demand is not enough to explain why there might be a risk of supply shortages in the future. Only comparing that, there does not seem to be a problem. The issue lies to a large extent in geopolitics, technology development, police targets and economic factors.

The TA was used as an inspiration for the view of the discussion. Many nations nowadays see rare earths as strategic materials, not the least because they are often used in military applications. The interest in this matter was mainly to investigate if rare earths could constrain the industry of electric vehicles in the future.

This report provides quite a broad perspective. Since a few tools have been combined none of them have been executed thoroughly. In a way this has been both good and bad. It has been good in the way that the snapshot picture the report was aimed to provide is quite inclusive when it comes to information about the product chains. The bad thing is that the report sometimes lacks depth in information about specific topics, it is up to the reader to further investigate special interests. This report will not provide any new information that did not already exist; it has rather collected information from many sources to provide an overall picture of the current situation. However, that is in line with the aim of this report. So in all the authors of this report feel that the right method was used in order to fulfill the purpose and it has been easy to work with the method as it is customized by combining several tools which all had fitting characteristics.

Some problems in the research had to do with finding information. Since there were no existing works with the same purpose as this report, information had to be collected from many different sources to complete the picture that it wanted to provide. This is why so many different sources have been used: scientific papers, books, news media, organizational information and reports, governmental information, company information, interviews with selected people, and blogs. The internet has been a very useful tool to get in contact with the information sources. E-mail correspondence has been frequently used to acquire information. This method has worked very well with people from Europe and the Americas, and not at all with people from Asia. This probably has a lot to do with cultural differences, and how we do contact. It could have been useful to actually travel to China or Japan, or visit conferences where we could have gotten in touch with people in person. However, that was not a possibility since there was no finance for this. And of course the actors involved in the chain would not provide confidential company information, which left us with annual reports or other public information.

Another problem was constant stream of new information. A lot is happening within this area at the moment, so to have the latest updated information meant that text that was written in the beginning of the project of this report has to be revised and corrected later. It was also difficult to screen the information flow for accurate information.

8 Conclusions

Demand for rare earths will most likely keep growing in the next coming years. There are many applications for rare earths due to unique qualities; they are especially suitable for green technologies where they can improve performance and reduce weight.

There is a risk of some rare earth elements running short in the future. If large scale wind power stations increase in number along with other technologies using the same elements, risks are that not even with a growing mining industry the demand will be met.

The elements that are most likely to become deficit are neodymium, dysprosium and terbium. This would probably be an effect much related to a growing production of permanent magnets using these elements, and also to the fact that these elements only occur in small percentages in the REO of many deposits in the world.

Today there are few producers outside of China. Most of the intellectual capital is therefore also in China today. Nevertheless, there will probably be outside-China production within next three years. Intellectual capital is attained through merger and acquisition between companies with different competency.

Since no official trade market exists today it is common that there are joint ventures, part ownerships or other agreements between companies in the different steps of the production chain. This is a way to secure business. For the rare earth producers this is important since their operations are very costly. For the manufacturers of rare earth containing products this is important because it would be very costly if they could not get their supply.

With the mining projects that are underway today the predicted demand of TREO is likely to be met. The issue of deficit will probably just apply to some of the elements; those that are used in the NdFeB permanent magnets are among those.

The reserves known today are likely to increase in the future. According to the definition of reserves they only include those parts of a resource that can be economically recoverable with existing technology. Since the price of some rare earth elements have escalated during the last years the profitability of mining has improved, which might in the future weigh up for high extraction costs. There are also uncertain signs that discoveries of new deposits have been made in countries like Afghanistan and Pakistan, which could add to the reserves.

There are many co-operations and joint ventures in the product chains that were analyzed in this report. This has to do with the lack of an official trade of rare earths today and the restrictions of patent rights for production.

Rare earths will probably not be a constraining factor for battery production for electric vehicles (HEVs and PEVs) since the lithium ion battery is predicted to be the preferred/dominating alternative in the future (the question whether there is enough lithium that can be produced in a sustainable way is outside the scope of this report). However, if the NiMH battery production for hybrids and electric vehicles would increase, which is plausible with an expected growth in the HEV/PEV market, the elements at risk would probably be neodymium (because of competition from permanent magnets) and praseodymium (because of low concentration in the REO of most deposits). Also, the transition to Li-ion batteries will take decades.

The competition from other technologies comes mostly from wind power and technological devices like computers and audio systems. Wind power plants use several hundred kilos of rare earths while other technologies such as computers and audio systems only use a few grams per unit. However, the smaller technological devices compared to wind power plants come in many times higher quantities which creates large amounts of rare earths bound in those products.

Recycling and recovery of rare earth materials might present a good alternative to mining virgin material. There are large in-use stocks of rare earths; most of the hybrid vehicles containing large amounts of them are still on the roads. The technology for recycling needs to be developed, together with infrastructure for collecting the discarded products, and become cost efficient.

9 References

Advanced Technology & Materials Co., Ltd (AT&M), 2011. [online] Available at: http://www.atmcn.com/en/ [Accessed 22 February 2011]

Alkane Resources Ltd., 2009. *Annual Report 2009*. [online] Available at: http://www.alkane.com.au/reports/annual/. [Accessed 14 March 2011]

AP, 2011. *Lynas defends rare earths refinery amid radioactive pollution 'threat'*. [online] The Australian, 11 Mar. Available at: http://www.theaustralian.com.au/business/mining-energy/lynas-defends-rare-earths-refinery-amid-radioactive-pollution-threat/story-e6frg9df-1226019588317 [Accessed 24 March 2011]

Arafura Resources Ltd., n/d. [company webpage] Available at: http://www.arafuraresources.com.au/ [Accessed 24 March 2011]

Avalon Rare Metals Inc., 2010. *Prefeasibility Study*. [company webpage] Available at: http://avalonraremetals.com/projects/thor_lake/prefeasibility_study/ [Accessed 30 March 2011]

Baotou-China. Available at: www.baotou.gov.cn [Accessed 18 March 2011]

Baotou National Rare Earth Hi-Tech Industrial Development Zone. [website] Available at: http://www.rev.cn/en/abo.htm [Accessed 5 March 2011]

Bauer, D., Diamond, D., Li, J,. Sandalow, D., Telleen, P. and Wanner, B., 2010. *Critical Materials strategy*. U.S. Department of Energy. [PDF]. Available at: http://www.energy.gov/news/documents/criticalmaterialsstrategy.pdf [Accessed 14 April 2011]

Baumann, H., Tillman, A-M., 2004. *The Hith Hiker's Guide to LCA*. Lund: Studentlitteratur AB. Chapter 1.

Beijing Jingci Magnetism Technology Co. (BJMT), 2005. [online] Available at: http://www.bjmt.com.cn/index.htm [Accessed 22 February 2011]

BGS, 2010. *Rare Earth Elements*. British Geological Survey. Available at: http://www.bgs.ac.uk/research/highlights/rare_earth_elements.html [Accessed 2 February 2011]

Boons, F., Howard-Grenville, J.A., 2009. *The social embeddedness of industrial ecology*. Cheltenham, UK, Edward Elgar Pub.

BPC, 2010, Brewton-Parker College. *History of the Development of the Periodic Table of Elements*. Brewton-Parker College, Math & Natural Sciences. [online] Available at: http://www.bpc.edu/mathscience/chemistry/history_of_the_periodic_table.html [Accessed 10 June 2011]

Brunner, P.H., Rechberger, H., 2004. *Practical handbook of material flow analysis*. Boca Raton: CRC Press.

Bubar, D., 2011. *Corporate presentation*. Avalon Rare Metals Inc. May 4. Available at: http://avalonraremetals.com/_resources/presentation/Corporate_Presentation_11_05_04.pdf [Accessed 18 May 2011]

Buchert, M., Dittrich, S., Liu, R., Merz, C., Schüler, D., 2011. *Final Report for The Greens/EFA Group in the European Parliament*. [online] Darmstadt: Öko-Institut e.V. Available at: http://reinhardbuetikofer.eu/wp-content/uploads/2011/01/Rare-earths-study_Oeko-Institut_Jan-2011.pdf [Accessed 5 March 2011]

Buschow, K. H. J., 2001. *Magnets: Bonded Permanent Magnets*. Encyclopedia of Materials, [PDF] Science and Technology, page 1. Available through: ScienceDirect http://www.sciencedirect.com [Accessed 14 April 2011]

Castor, S.B., 2008. *Rare Earth Deposits of North America*. Resource Geology Vol. 58, No 4: 337-347. Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1751-3928.2008.00068.x/pdf [Accessed 27 March 2011]

Chegwidden, J., Kingsnorth, D., n/d. *Rare earths - a golden future or overhyped?* [ppt presentation] Roskill and IMCOA.

China Daily, 2011. *New rules likely to raise price of rare earths*. China Daily [online] April 13. Available at :http://www.china.org.cn/business/2011-04/13/content_22346970.htm [Accessed 18 April 2011]

China Mining, 2011. *China's rare earth exports down 9.3% in 2010*. China Mining Association, January, 21. Available at: http://www.chinamining.org/News/2011-01-21/1295590605d42850.html [Accessed 28 April 2011]

China.org.cn, 2011. *China sets rare earth output quota for 2011*. [online] April 1. Available at: http://www.china.org.cn/business/2011-04/01/content_22273486.htm [Accessed 28 April 2011]

Cilene, M., 2011 . Mensagem Falo Conosco INB. [e-mail] Message to Therese Eriksson (erithe@student.chalmers.se). Sent Wednesday 6 April 2011 20:02. Available at: https://sn2prd0102.outlook.com/owa/?ae=Item&a=Open&t=IPM.Note&id=RgAAAACFKZonKFV8SKZAj%2fmn2kkUBwBxVVCfurBdRKww3CSon%2b60AAAVIkd5AADJzTQF%2bXpXSoWgaypa7t%2fwAAABZS%2bZAAAJ&pspid=_1305902711821_939357989 [Accessed 7 April 2011]

Clenfield, J., Yasu, M., Biggs, S., 2010. *Hitachi Leads Rare Earth Recycling Efforts as China Cuts Access to Supply*. Bloomberg, 8 Decmeber 2010. Available at: http://www.bloomberg.com/news/2010-12-08/hitachi-recycles-rare-earth-as-china-crimps-supply.html [Accessed 15 April 2011]

Cordier, D. J. and Hedrick, J. B., 2010. *2008 Minerals Yearbook: RARE EARTHS.* [ADVANCE RELEASE] U.S. Geological Survey. [PDF] Available at: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2008-raree.pdf [Accessed 15 April 2011]

Dikshit, S., 2011. *India to resume rare earth exports*. [online] The Hindu, 19 Feb. Available at: http://www.hinduonnet.com/2011/02/19/stories/2011021960010200.htm [Accessed 24 March 2011]

Du, X. and Graedel, T. E., 2010. *Global In-Use Stocks of the Rare Earth Elements: A First Estimate*. Environmental Science & Technology, [PDF] Available through: Environmental Science & Technology http://pubs.acs.org/journal/esthag [Accessed 19 April 2011]

ECD, 2005. *Cobasys and Panasonic EV Energy Extend Cooperation and Agree to Expanded License Terms*. [online press release] 6 July. Available at: http://investor.shareholder.com/ovonics/releases.cfm [Accessed 4 April 2011]

Ekberg, C., 2011. Professor at Chalmers University of Technology. Questions and answers about recycling of R.E.M.s. [conversation] (Personal communication, 14 April 2011)

van den Ende. J., Mulder, K., Knot, M., Moors, E., Vergragt, P., 1998. *Traditional and Modern Technology Assessment: Toward a Toolkit*. Technological Forecasting and Social Change, 58, pages 5-21. Elsevier Science Inc.

Feng, H., 2006. *Rare Earth: Production, Trade and Demand*. Journal of Iron and Steel Research, International, Volume 13, Supplement 1, Pages 33-38. Available through: ScienceDirect http://www.sciencedirect.com [Accessed 15 April 2011]

Frontier Rare Earths Limited, 2011. *Developing a world-class rare earth deposit in South Africa*. [Project presentation] March 2011. Available at: http://www.frontierrareearths.com/pdfs/presentation/FrontierPresentationMar2011.pdf [Accessed 30 March 2011]

GCC, 2010. *Toyota Motor and partners start NiMH battery-to-battery recycling in Japan*. [online] Green Car Congress, 27 October 2010. Available at: http://www.greencarcongress.com/2010/10/tmc-20101027.html [Accessed 23 May 2011]

Gorman, S., 2009. *As hybrid cars gobble rare metals, shortage looms*. [online] Reuters, 31 August 2009. Available at: http://www.reuters.com/article/2009/08/31/us-mining-toyota-idUSTRE57U02B20090831 [Accessed 11 May 2011]

Greenland Minerals and Energy Ltd, 2011. *Company Presentation*. [online]March 2011. Available at: http://www.ggg.gl/userfiles/Greenland-Presentation-March-2011-condensed.pdf [Accessed 20 March 2011]

GS-Yuasa Corporation, 2009. Annul Report 2009. [online] Available at: http://www.gs-yuasa.com/us/ir/pdf/GYCAnnual2009.pdf [Accessed 8 May 2011]

Gupta, C.K., Krishnamurthy, N., 2005. *Extractive metallurgy of rare earths*. Boca Raton, Florida, CRC Press.

GWMG, 2010. *Hoidas Lake, Saskatchewan*. [project information] 27 Jan, 2010. Available at: http://www.gwmg.ca/html/projects/hoidas-lake/index.cfm [Accessed 30 March 2011]

GMWG, 2011a. *Steenkampskraal Mine South Africa*. [Project information on company website] March 2011 Available at: http://www.gwmg.ca/html/projects/Steenkampskraal_Mine/index.cfm [Accessed 30 March 2011]

GMWG, 2011b. Great Western Minerals Group in Advanced Discussions on Rare Earth Separation Plant. [press release] 24 Feb, 2011. Available at: http://www.gwmg.ca/html/media/news/index.cfm?ReportID=203374 [Accessed 30 March 2011]

Haxell, G. H., 2002. Rare Earth Elements – Critical Roesources for High Technology [online] U.S. Geological Survey. Available at: http://pubs.usgs.gov/fs/2002/fs087-02/ [Accessed 23 March 2011]

Hitachi Metals, Ltd., 2007. Sintered Nd-Fe-B Magnets: The Patent and License Situation. Place of publication: http://www.hitachi-metals.co.jp/pdf/pi20070401ec.pdf [Accessed 13 March 2011]

Houses of Parliament, 2011. *Rare Earth Metals*. Parliamentary Office of Science & Technology. Post note number 368, Janury 2011. Available at: www.parliament.uk/post

Humphries, M., 2010. *Rare Earth Elements: The Global Supply Chain*. Federation of American Scientists, [PDF] Available at: http://www.fas.org/sgp/crs/natsec/R41347.pdf [Accessed 15 April 2011]

Hurst, C., 2010. *China's Rare Earth Elements Industry: What can we learn?*. [online] Institute for the Analysis of Global Security. March 2010. Available at: http://fmso.leavenworth.army.mil/documents/rareearth.pdf [Accessed 18 April 2011]

INB, 2011. *INB Buena – Mineral Treatment Unit*. [company webpage] Available at: http://www.inb.gov.br/inb_eng/WebForms/interna.aspx?secao_id=62 [Accessed 7 April 2011]

Ito, M., Kashiwaya, K., Sumiya, N., Hiroyoshi, N. and Tsunekawa, M., 2009. *Anode activating agent recovery by magnetic separation from the <0.075mm fraction of crushed nickel metal hydride batteries from hybrid vehicles*. Separation and Purification Technology, [PDF] Available through: ScienceDirect http://www.sciencedirect.com [Accessed 18 April 2011]

Kim, J., Korinek, J., 2010. *Export restrictions on strategic raw materials and their impact on trade and global supply*. OECD Trade Working Paper No. 95. TAD/TCWP(2009)27/FINAL. 29 March. Available at: http://www.oecd.org/trade

Kroll, G., gkroll@magnequench.com, 2011. *Patents, licenses and rare earths*. [email] Message to D. Olsson (olssond@student.chalmers.se). Sent Sunday 27 February 2011 08:47. Available at: https://sn2prd0102.outlook.com/owa/ [Accessed 14 April 2011]

Kuhrt, K., 1995. *Processing of permanent magnet materials based on rare earth-transition metal intermetallics*. [online] Intermetallics, Volume 3, Issue 4, pages 255-263. Available through: ScienceDirect http://www.sciencedirect.com [Accessed 14 April 2011]

Latifah, A., Meor Yusoff, M.S., 2002. *Rare Earth Processing in Malaysia: Case Study of ARE and MAREC Plants*. Vol. 1: 287-295. Proceedings of the Regional Symposium on Environment and Natural Resources. Kuala Lumpur, Malaysia 10-11 Apr 2002. Available at: http://www.ukm.my/rsenr3/rsenr1/P287-295.pdf [Accessed 25 March 2011]

Lehner, T., 2011. At Rönnskärsverket Boliden. Questions and answers about recycling of R.E.M.s and possibilities within Sweden. [phone call and email] (Personal communication, 13 April 2011)

LEJ, 2010. *Lithium Energy Japan Commits to Construction of New Plant*. [online] Lithium Energy Japan. News Release, 14 April. Available at: http://www.gs-yuasa.com/us/attention/pdf/20100414e.pdf [Accessed 8 May 2011]

Li, L., Xu, S., Ju, Z. and Wu F., 2009. *Recovery of Ni, Co and rare earths from spent Ni–metal hydride batteries and preparation of spherical Ni(OH)2*. Hydrometallurgy, [PDF] Available through: ScienceDirect http://www.sciencedirect.com [Accessed 19 April 2011]

London, I., 2010. *The delicate supply balance and growing demand for rare earths*. [presentation] Avalon Rare Metals Inc., January 27. Magnetics 2010, Orlando, Florida. Available at: http://avalonraremetals.com/_resources/IL_010.01_Magnetics.pdf [Accessed 18 May 2011]

Lynas Corporation, 2010. *Quarterly Report for the Period Ending 31 December 2010*. [online] Available at: http://www.lynascorp.com/content/upload/files/Q4_2010_Quarterly_Report_-_FINAL_FINAL.pdf [Accessed 30 March 2011]

Lynas Corporation, 2011. *Rare Earths We Touch Them Every Day*. [Investor Presentation] March 2011. Available at: http://www.lynascorp.com/content/upload/files/Presentations/Investor_Presentation_March_2011_950850.pdf [Accessed 27 March 2011]

Magnusson, M., 2011. *LKAB undersöker apatit och jordartsmetaller*. LKAB, Available at: http://www.lkab.com/?openform&id=31CA&visaid=1A82A [Accessed 24 April 2011]

Maruo, K., 2011. *Neodym i NiMH batterier*.[e-mail] Message to Therese Eriksson (erithe@student.chalmers.se). Sent Monday 4 April 2011 11:53. Available at: https://sn2prd0102.outlook.com/owa/?ae=Item&a=Open&t=IPM.Note&id=RgAAAACFKZonKFV8SKZAj%2fmn2kkUBwBxVVCfurBdRKww3CSon%2b60AAAVIkd5AADJzTQF%2bXpXSoWgaypa7t%2fwAAABZS%2bXAAAJ&pspid=_1305712469299_367760468 [Accessed 4 April 2011]

MEP, 2010. *Stricter Environmental Standards for Rare Earth Mining*. [online] Ministry of Environmental Protection The People Republic of China. Media News, November 8. Available at: http://english.mep.gov.cn/News_service/media_news/201011/t20101108_197248.htm [Accessed 28 April 2011]

MOFCOM, 2011a. *China plans to take lead in new-energy vehicles*. [online] Ministry of Commerce People's Republic of China, April 8. Available at: http://english.mofcom.gov.cn/aarticle/newsrelease/counselorsoffice/westernasiaandafricareport/201104/20110407489135.html [Accessed 28 April 2011]

MOFCOM, 2011b. *Rare earth prices surge in China*. [online] Ministry of Commerce People's Republic of China, March 31. Available at: http://english.mofcom.gov.cn/aarticle/newsrelease/counselorsoffice/westernasiaandafricareport/201103/20110307476907.html [Accessed 28 April 2011]

MOFCOM, 2011c. *State-planned rare earth mining zones aim for sustainable use, environmental protection*. [online] Ministry of Commerce, 11 Feb. Available at:

http://english.mofcom.gov.cn/aarticle/counselorsreport/asiareport/201102/20110207395538.html [Accessed 23 March 2011]

Molycorp Minerals, 2009. *Global outlook*. [online] Available at: http://www.molycorp.com/globaloutlook.asp [Accessed 27 March 2011]

Molycorp, 2010. *Annual Report*. [online] Available at: http://www.molycorp.com/2010annualreport/index.html [Accessed 3 June 2011]

Najafizada, E., 2011. *U.S., Afghan Study Finds Mineral Deposits Worth $3 Trilion*. [online] Bloomberg, 29 Jan. Available at: http://www.bloomberg.com/news/2011-01-29/u-s-afghan-study-finds-mineral-deposits-worth-3-trillion.html [Accessed 23 March 2011]

Neo Material Technologies, 2009a. *Neo Material Technologies Signs Development Agreement for Brazilian Rare Earth Deposit*. [online news release] 15 April, 2009. Available at: http://www.neomaterials.com/assets/content/ir/ir_press/a303/a376/Neo_Press_Rel_15April09.pdf [Accessed 4 April 2011]

Neo Material Technologies, 2009b. *Neo Material Technologies Signs Agreement with Mitsubishi Corporation for the Development of the Pitinga Rare Earth Resource*. [online news release] 21 July, 2009. Available at: http://www.neomaterials.com/assets/content/ir/ir_press/a303/a406/Neo_Press_Rel_21July09.pdf [Accessed 1 April 2011]

Neorem Magnets, 2009. [online] Available at: http://www.neorem.fi/ [Accessed 22 Februari 2011]

Nikkei, 2010. *Shin-Etsu Chem To Recycle Rare-Earth Metals From Appliances*. Nikkei, [online article] Published Saturday 9 October 2010, Available at: http://e.nikkei.com/e/fr/tnks/Nni20101008D08JFF02.htm [Accessed 20 april 2011]

Ningbo Yunsheng High-Tech Magnetics Co., Ltd., 2005. [online] Available at: http://www.yunshengmagnet.com/ecompany.htm [Accessed 22 February 2011]

Resende, L. V. and Morais, C. A., 2010. *Study of the recovery of rare earth elements from computer monitor scraps – leaching experiments*. Minerals Engineering, [PDF] Available through: ScienceDirect http://www.sciencedirect.com [Accessed 19 April 2011]

Richardson, M., 2010. *Preliminary Economic Assessment (Scoping Study) of the Beal Lodge Rare-Earths Project – a National Instrument 43-101 Report*. [technical report] November 2011, Report No. 3431.001. Available at: http://www.rareelementresources.com/i/pdf/110910-Rare-Element.pdf [Accessed 30 March 2011]

Roy, R., Mukherji, B., 2010. *India plans to step up miningof rare earth minerals*. [online] The Wall Street Journal, 3 Nov. Available at: http://online.wsj.com/article/SB10001424052748703506904575591891058707672.html [Accessed 24 March 2011]

Sadden, E., 2011. *New Push to Recycle REMs*. Pike Research Blog. Published 10 March 2010, Available at: http://www.pikeresearch.com/blog/articles/new-push-to-recycle-rems [Accessed 20 April 2011]

Sastri, V.R., Perumareddi, J.R., Ramachandra Rao, V., Rayudu, G.V.S. and Bunzli, J.-C., 2003. *Modern Aspects of Rare Earths and Their Complexes*. [pdf] Available at: <http://www.sciencedirect.com.proxy.lib.chalmers.se/science/book/9780444510105> [Accessed 11 April 2011]

Schramberg Magnet- und Kunststofftechnik GmbH, 2011. [online] Available at: http://www.magnete.de/ [Accessed 22 Februari 2011]

Serova, 2011. Questions about rare earths.[e-mail] Message to Therese Eriksson (erithe@student.chalmers.se). Sent Wednesday 30 March 2011 13:31. Available at: https://sn2prd0102.outlook.com/owa/?ae=Item&a=Open&t=IPM.Note&id=RgAAAACFKZonKFV8SKZAj%2fmn2kkUBwBxVVCfurBdRKww3CSon%2b60AAAVIkd5AADJzTQF%2bXpXSoWgaypa7t%2fwAAABZS%2bOAAAJ&pspid=_1305902711821_939358240 [Accessed 30 March 2011]

Shen, I., 2011. *China Vanke, ICBC, Inner Mongolia Baotou: China Equity Preview*. [online] Bloomberg News, 17 Feb. Available at: http://www.bloomberg.com/news/2011-02-16/china-vanke-icbc-inner-mongolia-baotou-china-equity-preview.html [Accessed 23 March 2011]

ShinEtsu Rare Earth Magnets, 2007. [online] Available at: http://www.shinetsu-rare-earth-magnet.jp/e/ [Accessed 22 Februari 2011]

Schreffler, R., 2010. *Growth of Hybrid, Evs Leads to Expanding Global Supplier Base*. [online] Penton Media, 23 August. Available at: http://www.wardsauto.com/ar/hybrid_electric_supplier_100823/index.html [Accessed 5 May 2011]

Smith, M., 2010. *Rare earth minerals: the indispensable resource for clean energy technologies*. [online] Conference presentation. Technology and rare earth metals 2010, Washington DC, March 17. Available at: http://www.tremcenter.org/index.php?option=com_attachments&task=download&id=16 [Accessed 12 May 2011]

Sumitomo Corp., 2009. *Sumitomo Corporation embarks on a rare-earth recovery project in the Republic of Kazakhstan*. [News Release] 12 Aug 2009. Available at: http://www.sumitomocorp.co.jp/english/news/2009/20090812_082824.html [Accessed 29 March 2011]

Takeda, O., Okabe, T. H., Umetsu, Y., 2005. *Recovery of neodymium from a mixture of magnet scrap and other scrap*. Journal of Alloys and Compounds, [PDF] Available through: ScienceDirect http://www.sciencedirect.com [Accessed 18 April 2011]

Tasman Metals, 2011. *Tasman påbörjar en tredje fas av borrningar vid Norra Kärr*. [online] Tasman Metals Ltd. News release, January 19. Available at: http://www.tasmanmetals.com/i/pdf/NR-SWE/2011-01-19_SWE_NR.pdf [Accessed 12 May 2011]

TDK Corporation, 2011. [online] Available at: http://www.global.tdk.com/ [Accessed 22 February 2011]

Tengzelius, J., 2011. At Höganäs. Questions and answers about the product chain of R.E.M.s, globally and possibilities within Sweden. [phone call] (Personal communication, 13 April 2011)

Thinova Co., Ltd., 2009. [online] Available at: http://www.thinova.com/en/index.asp [Accessed 22 February 2011]

Toyota, 2009. *2010 Prius Plug-in Hybrid Makes North American Debut at Los Angeles Auto Show*. [press release] 2 Dec, 2009. Available at: http://pressroom.toyota.com/article_display.cfm?article_id=1822 [Accessed 6 April 2011]

Toyota, 2010. *Worldwide 'Prius' Sales Top 2-million Mark*. Toyota homepage, published 7 October 2010. Available at: http://www2.toyota.co.jp/en/news/10/10/1007.html [Accessed 11 May 2011]

Toyota, 2011. Toyota sells one-millionth Prius in the U.S. [news release] 6 April. Available at: http://pressroom.toyota.com/article_display.cfm?article_id=2959 [Accessed 5 May 2011]

USGS, 2010. *The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective*. [online] Virginia: US Geological Survey. Available at: http://pubs.usgs.gov/sir/2010/5220/ [Accessed 15 February 2011]

USGS, 2011. *Annual publication: Mineral Commodity Summaries: Rare Earths: 2011*. [online] Available at: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/ [Accessed 14 March 2011]

Vacuumschmelze GmbH, 2010. [online] Available at: http://www.vacuumschmelze.de/ [Accessed 22 February 2011]

Vereschagin, YU.A. et al., 2006. *Rare-Earth Magnets in Russia: Raw Materials, Processing, Properties Control and Output Issues*. Journal of Iron and Steel Research, International, Volume 13 pp.23-32. [online] (published: 2008-11-06) Available through SciVerse database. [Accessed 25 January 2011]

Vulcan, T., 2008. *Rare earth metals: not so rare but still valuable*. HardAssetInvestor.com [online] (published: 2008-11-04) Available at: http://www.hardassetsinvestor.com/features-and-interviews/1266-rare-earth-metals-not-so-rare-but-still-valuable.html?start=1 [Accessed 14 March 2011]

Weihed, P., 2011. Professor at LTU. Questions and answers about the product chain of R.E.M.s, globally and possibilities within Sweden. [phone call] (Personal communication, 13 April 2011)

Yap, C-W., 2011. *China rare earth export rise*. [online] Wall Street Journal, May 21. Available at: http://online.wsj.com/article/SB10001424052748704816604576336351109861400.html?mod=googlenews_wsj [Accessed 25 May 2011]

Zelinsky, M., Koch, J., Fetcenko, M., 2010. *Heat Tolerant NiMH batteries for Stationary Power*. [online] Ovonic Battery Company. Available at: http://libweb.anglia.ac.uk/referencing/harvard.htm [Accessed 4 April 2011]

Zhanheng, C., 2010. *Speech at the 6th International Rare Earths Conference*. November 9-11, Hong Kong, China. Available at: http://www.cs-re.org.cn/ChinaRE2010-11-9-ZhanhengWork.pdf

Zhanheng, C., 2011a. *Global rare earth resources and scenarios of future rare earth industry*. Journal of Rare Earths, Volume 29, No 1. Available through ScienceDirect database. [Accessed 5 March 2011]

Zhanheng, C., 2011b. *China's role in a changing global rare earths market*. [online] Presentation from Critical Metals Investment Summit, Vancouver, Canada, January 21-22. Available at: http://www.lynascorp.com/content/upload/files/Industry_Articles/CSRE_Presentation_FINAL.pdf [Accessed 12 May 2011]

Zhong Ke San Huan, 2009. [online] Available at: http://www.san-huan.com.cn/ [Accessed 22 February 2011]

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11 Appendix

	Mountain Pass	Bayan Obo	Lehat	Lognan	Xunwu
Lanthanum	19,3	23,0	1,2	1,8	43,4
Cerium	39,2	50,0	3,1	0,4	2,4
Praseodymium	3,8	6,2	0,5	0,7	9,0
Neodymium	15,5	18,5	1,6	3,0	31,7
Samarium	2,8	0,8	1,1	2,8	3,9
Europium	0,6	0,2	-	0,1	0,5
Gadolinium	1,7	0,7	3,5	6,9	3,0
Terbium	0,3	0,1	0,9	1,3	-
Dysprosium	1,7	0,1	8,3	6,7	-
Holmium	0,4	-	2,0	1,6	-
Erbium	1,3	-	6,4	4,9	-
Thulium	0,2	-	1,1	0,7	-
Ytterbium	0,9	-	6,8	2,5	0,3
Lutetium	0,2	-	1,0	0,4	0,1
Yttrium	12,3	-	61,0	65,0	8,0
Sources	(USGS)	(USGS)	(USGS)	(USGS)	(USGS)

	Kutessay II	Mount Weld	Steenkamp skraal	Brazil	Nolans	Zandkopsdrift	Nechalacho
Lanthanum	9,4	25,5	21,7	24,0	19,7	25,4	15,8
Cerium	25,9	46,7	46,6	47,0	47,5	44,2	35,7
Praseodymium	3,3	5,3	5,0	4,5	5,8	4,6	4,5
Neodymium	8,8	18,5	16,7	18,5	21,2	15,8	17,8
Samarium	3,9	2,3	2,5	3,0	2,4	2,3	3,9
Europium	2,6	0,4	0,1	0,1	0,4	0,6	0,5
Gadolinium	2,8	-	1,6	1,0	1,0	1,4	3,7
Terbium	1,2	0,1	0,1	0,1	0,1	0,2	0,5
Dysprosium	6,5	0,1	0,6	0,4	0,3	0,8	2,7
Holmium	1,2	-	0,1	-	1,3	0,1	0,5
Erbium	5,0	-	0,1	0,1	0,2	0,3	1,3
Thulium	0,05	-	0,1	-	0,1	-	0,2
Ytterbium	1,8	-	0,1	-	0,1	0,2	1,0
Lutetium	0,06	-	-	-	-	-	0,1
Yttrium	27,6	-	5,0	1,4	1,3	4,1	11,7
Sources	(Stans Energy Ltd)	Lynas Corp	Great Western Minerals Group	(USGS)	(Arafura Resources)	(Frontier Rare Earths)	Avalon Rare Earth Metals