Rare Metals: Energy Security and Supply

Hanna Vikström
Abstract

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Lithium and neodymium are two critical materials in our modern society, many technological solutions depend on them. Lithium is used in batteries, which are used in cars and portable electronics. Neodymium, which is a rare earth element, is mainly used in permanent magnets which are used in smartphones, hard disc drives and turbines. There are many reports regarding the availability of the metals, with different results. The available data on the reserves varies considerably, from the few sources there are. In this report, based on geological availability, forecasts are done to investigate how much the production can increase and when it will peak. The prognoses are based on historic production to which different functions, the logistic, gompertz and richards, are fitted with the least square method. The production will peak in the end of this century and in the beginning of the next century for both metals. The production of lithium does not seem to be sufficient for both producing electric and hybrid cars with only li-ion batteries along with fusion. The neodymium production will be sufficient for producing a lower percentage of direct driven wind turbines and electric cars with NIMH batteries. Lithium in seawater is sometimes considered a future source. Since the lithium concentration is low, large volumes have to be processed in order to extract a reasonable amount of lithium. Currently it is not economic to extract lithium from seawater.
Populärvetenskaplig sammanfattning


För att kunna göra prognoser angående framtida produktion behövs data för historisk produktion och data för reserverna, hur mycket som är möjligt att tekniskt och ekonomiskt utvinna ur marken. Det finns in konsistenta siffror över uppskattningarna av reserverna beroende på olika rapporteringsstandarder och definitioner.


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## Abbreviations

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<tr>
<td>BGS</td>
<td>British Geological Survey</td>
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<tr>
<td>CIS</td>
<td>Commonwealth of Independent States</td>
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<tr>
<td>DOE</td>
<td>Department of Energy, USA</td>
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<tr>
<td>EV</td>
<td>Electric Vehicle</td>
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<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
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<td>HREE</td>
<td>Heavy Rare Earth Element</td>
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<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>LCE</td>
<td>Lithium Carbonate</td>
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<tr>
<td>LREE</td>
<td>Light Rare Earth Element</td>
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<tr>
<td>NiMH-battery</td>
<td>Nickel Metal Hybrid battery</td>
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<tr>
<td>PHEV</td>
<td>Plug in Hybrid Electric Vehicle</td>
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<td>REE</td>
<td>Rare Earth Element</td>
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<td>REM</td>
<td>Rare Earth Mineral</td>
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<td>REM</td>
<td>Rare Earth Mineral</td>
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<td>REO</td>
<td>Rare Earth Oxide</td>
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<tr>
<td>SGU</td>
<td>Geological Survey of Sweden</td>
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<tr>
<td>URR</td>
<td>Ultimately Recoverable Resources</td>
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<td>USGS</td>
<td>U.S Geological Survey</td>
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1. Introduction

The major constraint to economic and population growth will be mineral resources (Van Rensburg, 1975). In this thesis supply and demand of two metals, lithium and neodymium will be investigated. Mineral resources are used to create a modern society with high standards such as ours. The resources are finite and depletion will be a threat to our way of living. It is important to do research and forecasts about the future availability of mineral resources. Most of the research about the availability is prognoses of 10 – 20 years into the future, therefore a longer forecast is needed to investigate if these minerals will be available for future use before applications and needs are based on them. Is it possible to reduce our need for oil by using more minerals instead?

The supply of lithium and neodymium will be forecasted by fitting different curve models to the historic production. The forecasts will stretch to year 2100. The data used will only be free public data. Neodymium is a rare earth element (REE) and constitutes a large part of the REE production. It is mainly used in permanent magnets for applications such as generators, hard discs drives, smartphones and in NiMH batteries. Lithium is used in many applications such as batteries, ceramics and potentially also fusion and global consumption is increasing. Is there enough of these metals for all the applications in the future? Enough to exchange the transport sector to electric and hybrid vehicles, fusion and wind turbines, or is the availability of metals a bottleneck for future high technology production? The availability of mineral resources is an essential energy security question, especially for the REEs since China has over 90 % of the current production, can every country secure their need of mineral resources? The rare earth elements could play a very important role in our society. Deng Xiaoping said in 1992 “There is oil in the middle east. There is rare earth in China” (Levkowitz, 2010).

The demands for minerals are growing but sadly there is not much concern regarding the depletion of minerals. The main concern is the consequences of using the mineral resources such as pollution and climate changes (Valero and Valero, 2010). It is only recently that research has been looking into cost of production due to physical and economic resource depletion (Prior et al, 2011). Therefore it is important to extend the research regarding peak minerals and make some prognosis about the future availability regarding the elements lithium and neodymium.

Even in popular culture depletion, extractions of mineral resources are becoming an issue. For example in the latest James Bond movie, “Quantum of solace” is about securing the water supply to the people in Bolivia. This is based on a real problem; the lithium extraction in South America, which needs large amounts of fresh water. Bolivia has the world's largest lithium resources but not yet any lithium production. If production were to start, the water supply could become an immediate problem for the local population. The western world doesn’t want to decrease their living standards, therefore the mineral exploitation will continue. Mineral exploitation results in environmental consequences for the countries with the most mineral resources, usually poor countries. These problems are largely political. Both the European Commission, (2010), and the U.S Department of Energy, (DOE, 2011), have been doing research regarding elements which are crucial for our society. Both of them have classified the supply of REE as critical in the next 5 years, especially the elements dysprosium, yttrium, neodymium and terbium. The REE production is dominated by China which is not a reliable supplier. Recycling is almost nonexistent. Lithium is an important element in our society with a supply risk, see figure 1, though the risk is now as high as for REE (Schuler et al, 2011).
As seen in figure 1, there are many metals with a supply risk, lithium and neodymium are chosen because of their role in the modern society. REEs are already experiencing shortage, and since neodymium is one of the most crucial metals and also the largest part of the REE production it is natural to investigate further. (DOE, 2011) Lithium is needed in many applications and for a society to be able to reduce their CO₂ consumption. Electric and hybrid vehicles are important in which lithium batteries are needed. There is a large debate regarding the amount of lithium resources and reserves (Evans, 2008, Tahil, 2007), thus it is important to highlight the difficulties in determining them. The society depends on these metals and research regarding these metals is missing, it is just taken for granted that they will be available.

As with many metals it is possible to exchange lithium and neodymium to other metals, but the performance will not be as good. The magnetic properties of neodymium are not found in other materials and therefore difficult to replace. It is currently impossible to replace the metals and still have the same performance and size.
1.1 Usage of Lithium

Lithium was first discovered in 1817 by the Swede Johan August Arfwedson in the mineral petalite on Utö, Sweden. Lithium is used in a range of products, the end use products are; ceramics and glass, 31%; batteries, 23%; lubricating greases, 9%; air treatment, 6%; primary aluminum production, 6%; continuous casting, 4%; rubber and thermoplastics, 4%; pharmaceuticals, 2%; and other uses, 15%. (USGS, 2011a)

Lithium is used in a range of applications because it is one of the lightest metals and has a small ionic radius which makes it easy to fit into an already existing lattice. It is used to reduce the melting temperature in glass and ceramics and strengthening them. Also, lithium lowers the thermal expansion coefficient and can therefore make a material more stable due to change in temperature. It has a high electronegativity which gives it the highest electric output per unit weight that any battery currently has. Since lithium has a range of good properties the industry prefers it to other elements, often because of its size and weight. The lithium ion batteries are the best performing batteries today. The lithium consumption is expected to rise due to increased usage of lithium ion batteries in hybrid and electric vehicles, and potentially in fusion, if it is commercialized (Ebensperger et al, 2005, Garrett, 2004).

1.1.1 Batteries

The first commercialized lithium battery was not produced until 1991, even though it was proposed already in the 1970’s. Now batteries are the second largest area of usage and the demand is increasing. In the battery the lithium ions are moving from the negative to the positive electrode when discharging and the opposite when charging. The lithium batteries are advantageous to other batteries due to their high energy and power density and slow discharging when not in use. Its lifetime could be as long as the car it would power, which makes it economically advantageous. There are alternatives to the lithium ion battery such as NiMH batteries which are cheaper to produce, although they have a lower power density and a shorter lifetime (Gaines, 2000).

In the US, the lithium content in camera batteries increased drastically from 100 kg in 1996 to 19 tons in 2005. For mobile phones the increase was from 1.8 tons to 170 tons and for laptops from 3.3 to 99 tons. Lithium ion batteries are replacing NiMH batteries in cell phones (Wilburn, 2008). The lithium content for one phone is about 0.3 g and for one laptop about 5.5 g (JOGMEC, 2009).
1.1.2 Lithium used in fusion power plants

Fusion has been discussed as a future energy source; the most favorable fusion reaction is colliding deuterium and tritium to create $^4$He. Deuterium exists in nature, while tritium does not, it has to be created, which is usually done by one of the two reactions:

$$^6\text{Li} + n \rightarrow ^4\text{He} + T + 4.8 \text{ MeV} \quad [1]$$
$$^7\text{Li} + n \rightarrow ^4\text{He} + T + n - 2.87 \text{ MeV} \quad [2]$$

The first reaction [1] is preferable since it creates energy while the other [2] reaction demands energy.

There are two different possibilities for fusion reactors; to use liquid lithium both as a coolant and as a breeder or using solid lithium as a blanket inside the reactor. If lithium is used as coolant and breeder, 787 tons is needed for a 1.5 GW power plant. If used as a blanket a smaller amount is needed, 174 tons for a 1.5 GW power plant (Fasel and Tran, 2005. The total amount of lithium spent during 8000 hours for a 1.5 GW plant would be in the range of 6.3 – 8.9 tons, so for one day 19 – 27 kg (Fasel and Tran, 2005). Smith et al (2010) conclude that a 1.5 GW plant would use about 10–20 kg of natural lithium and 0.6 kg of deuterium per day, for one year that would require 3.65 – 7.3 tons.

1.2 Usage of REE/Neodymium

Rare earth elements are not as rare as the name suggests, but are relatively common in low concentrations. Therefore it is usually not economically possible to mine them in except for a few large deposits. The rare earth elements are the lanthanides with atomic numbers 57 – 71 in the periodic table, scandium, 21, and yttrium, 39. The elements are marked in figure 3. Yttrium and scandium are included since they have similar properties. The elements were first discovered in Ytterby, Sweden by Carl Gustaf Mosander. The rare earth elements are divided into light and heavy elements. The light rare earth elements, LREE, are; La, Ce, Pr, Nd and heavy rare earth elements, HREE, are; Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Ku, Y. Light rare earth metals are about 75 % of the total production. (Chen, 2011)

Neodymium has specific properties which make it very commercially interesting, its magnetic properties are outstanding compared to other materials. There are 33 isotopes of neodymium, the most abundant isotope, is $^{142}\text{Nd}$, which makes up 27.2 % of the different isotopes.

![Figure 3, Periodic Table with rare earth elements, (USGS, 2002)](image-url)
The usage areas of REE are; glass industry, 22%; catalysts, 21%; neodymium magnets, 20%; battery alloys, 9%; Metallurgy except batteries, 9%; rare-earth phosphors, 7%; ceramics, 5%; and other, 6%. (Goonan, 2011)

The main usage of neodymium is permanent magnets. The total production of REO in 2008 was 129,000 tons, and the neodymium oxide production alone was 23,900 tons, 18.5 % of the total production. About 76 %, 18,200 ton, of the neodymium oxide was used for magnets. The rest was used in; metallurgy (except batteries) 8 %, battery alloys, 5 %, ceramics, 3.5 %, glass additives 1.5 %, automobile catalytic converters, 1 %, other applications 4.7 %. (Goonan, 2011)

![Neodymium usage](image)

**Figure 4, Neodymium usage (Goonan, 2011)**

### 1.2.1 Permanent magnets

Permanent magnets are the single largest area of rare earth usage, which includes the elements neodymium, samarium, praseodymium, terbium and dysprosium. The best permanent magnet on the market is a neodymium-iron-boron magnet (Nd$_2$Fe$_{14}$B). The permanent magnets do not only contain neodymium but also praseodymium and smaller amounts of dysprosium and terbium. Neodymium and praseodymium together make up about 30 % of the magnet and dysprosium an additional 3 % (Schuler et al, 2011).

The neodymium magnet has the highest energy product of all the permanent magnets, which makes it outstanding on the market. The magnets are about 2.5 times stronger than samarium cobalt magnets and 7 – 12 times stronger than aluminum iron magnets (Schuler et al, 2011). There are downsides to the magnets. They have a low corrosion resistance. To at least partly overcome that problem it is possible to change its inner structure by adding another rare earth element such as dysprosium. However the recycling costs are increased due to corrosion. Another disadvantage with the magnets is that the operating temperature is limited to below their curie temperature, 300-400 degrees Celsius (Muller, 2001). If dysprosium or terbium is added then the working temperature is increased (Goonan, 2011).

The future demand for permanent magnets are to the largest extent determined by three applications; wind turbines, electric vehicles and hard disc drives. Currently there are three different technologies of wind turbines available on the market. One of them is direct driven turbines, which uses permanent
magnets instead of a gear box which reduces maintenance cost and weight of the turbine. Direct driven turbines are currently 14 % of the market (Schuler et al, 2011). These turbines would be very advantageous to use offshore, where maintenance is more costly and problematic (Kleijn, 2010, Castor and Hedrick, 2006). Wind power is expanding and the demand for permanent magnets in wind turbines varies considerably depending on growth rate, share of gearless turbines and the amount of rare earths required per MW (Schuler et al, 2011).

Electric and hybrid vehicles use neodymium magnets and sometimes also NiMH batteries which contains neodymium. To which extent is almost impossible to say and the future for these vehicles and material use is uncertain. Furthermore magnets are also used in the industry for lifting or magnetic separation. Magnetic cooling could potentially become a future usage area for permanent magnets, it reduces energy consumption by 50 – 60 % compared to traditional compression techniques. The magnetic cooling is based on a magneto caloric effect. The process is based on a changing magnetic field which causes a reversible temperature change in the material that is exposed. If it becomes commercial then it could require a large amount of the production capacity (Schuler et al, 2011).
2. Reserves and resources

2.1 Introduction

There are many expressions regarding mineral estimations. Reserves, resources, in-situ and mineral endowment are some examples. It is crucial to know the difference between these different words and they are often confused which creates problems. To avoid that in this report the words will be defined in this chapter. Mineral endowment is a complex word with no clear definition and therefore it will not be used. It is better to use words with a clear definition, such as reserves and resources, which will be used in this report.

The definition of resources and reserves is not consistent everywhere which creates difficulties and confusion regarding the available amount of minerals. The UN has addressed the problem and tried to make a worldwide standard. However their attempt does not seem to have worked very well.

Resources are the amount that has reasonable prospect of being economically extracted. Reserves are the amount that is economically possible to extract. The information regarding reserves and resources can never be complete due to new discoveries and depletion of others. Therefore, it is almost impossible to predict the future reserves and resources exactly (Pan et al, 1992). In-situ resources or reserves are sometimes reported. In-situ resources are the amount of a mineral that is in the ground, in a deposit but it doesn’t have to be economically extractable. There is a definition of deposit made by CIM, Canadian Institute of Mining, Metallurgy and Petroleum, “a natural occurrence of mineral or mineral aggregate, in such quantity and quality to invite exploitation”. (CIM, 2003)

Abundance of certain elements in the earth’s crust does not say anything regarding the reserves and the possible production. Copper is less abundant than cerium, a rare earth element. However, the copper production is 16 200 million tons, whereas the REE production is 130 000 tons (USGS, 2011c). The copper production were almost 125 times larger than REE production. It is the concentration and the deposit size that matters not the abundance in the crust.

When discussing peak oil it is said that: it is not the size of the tank which matters but the size of the tap. The content of that is; it does not matter how much there is of a resource but what matters is how much we will be able to extract and at which pace. Even if there will be enough mineral resources it will not be possible to extract all of it due to other factors.

Reserves are dynamic and vary depending on many factors such as the available technique, economic demand, political issues and social factors. If the technique is improved it can be possible to extract more than earlier anticipated thus the reserve base is increasing. Similarly if the technique is not as good as anticipated or the price of the product is decreasing, the reserves will decrease. Environmental and political issues can also limit the production (Van Rensburg, 1975). Deposits that have been mined for some time can increase or decrease their reserves due to difficulties with determining the ore grade and tonnage in advance (Pan et al, 1992).

When estimating the amount of reserves in a deposit there is usually a cut-off frequency for the concentration, below which it is not economical to mine. A non-mined deposit has a high cut-off frequency not to overestimate the reserves. When more information is available, after mining for some time, it is possible to adjust the limit properly (Pan et al, 1992). Other problems that could occur is that the cut-off grade is set too high and therefore some economically extractable parts could be left in the deposit (Schuler et al, 2011).

The explorations of minerals have mainly been motivated by economic and social demands. A major deposit should be seen as rare since most of the mineral just exist in an insignificant amount in the earth’s crust. There are many ore deposits, but the production is mainly concentrated to a few giant
deposits, productions from small deposits are often almost negligible. Since the giant deposits dominate production and reserves, the economic viability is dependent on finding giant deposits. Estimation techniques for determining the reserves in a deposit are important. However these rare deposits do not have usual statistic properties and are therefore difficult to determine amount and concentration of metals (Pan et al, 1992).

To find a deposit the geological conditions have to be favorable. Thereafter the geology has to be mapped by different methods to further determine grade and tonnage. Earlier the mineral deposits were determined by qualitative methods and by geologists but today quantitative methods are used. A quantitative method collects a lot of data and afterward statistical methods are applied to the collected data. Qualitative methods are based on observations, and the data collected is determined in advance. The quantitative methods have to be improved to actually belong to the same sample scheme to get a representable probability distribution. Data is collected with different methods and are then creating different data densities, inconsistent spatial locations etc. It is also represented in different quantities which give rise to problems. Some of the data is unnecessary and other parts need to be filtered, which also causes problems since artefacts, undesired variations in data, can be created (Pan et al, 1992). There are physical-, chemical- and socioeconomic properties and demand to account for when determining if a mineral deposit is economically viable. Due to those factors, also qualitative methods have to be used in order to properly determine the economic conditions.

2.2 Resource/Reserve classification

There are many standards for reporting mineral reserves and resources, here are an example of some of them. Among these Crirsch and SAMREC could have been included, but Crirsch is based on the JORC code, see 2.2.3, and SAMREC is the system used in South Africa, therefore those are not as interesting for this report since most of the reserves are situated in South America and Asia. More can be read about them in SAMREC, (2009) and Crirsch, (2006).

2.2.1 UNFC

UNFC (United Nations framework classification for energy and minerals) have a different approach to mineral reserves and resources. The existing systems are not compatible and therefore they are developing a new system which they hope will become international, to make consistent estimations of resources and reserves. However the system is quite complex and differs from the others which make it difficult to use and the different mining companies already have systems and preferably want to keep them since they know the system. It takes into consideration; commercial projects, potentially commercial projects, non-commercial projects, exploration projects and additional quantities in place. (United Nations, 2009)

2.2.2 USGS

USGS has their own system of classifying mineral reserves and resources, see figure 5. (USGS, 2009c)

Resource: A concentration of naturally occurring elements in the earth’s crust. The amount must exist in such form and amount that economic extraction must be currently or potentially feasible.
**Identified resources:** Resources whose location, quality and quantity are known or estimated from specific geological evidence. It includes measured, indicated and inferred resources.

**Measured resources:** Quantity is computed from results of drillings, trenches, outcrops and workings. Grade and/or quality are computed from detailed samplings. The sites are located so closely to each other that size, shape, depth and mineral content is well established.

**Indicated resources:** Quality, quantity and grade are computed like measured resources, however not as thorough, the measurements are further apart however close enough for continuity to be assumed.

**Inferred resources:** Estimates of resources based on an assumption of continuity beyond the measured and/or indicated resources, for which there are real geological evidence. Inferred resources do not have to be supported by samples or measurements but they can be.

**Reserve Base:** The part of a resource that meets specified minimum physical and chemical criteria related to current mining and production practices, such as quantity, quality, grade and depth. The reserve base is the demonstrated (measured + indicated) resources. It includes those resources that could become economically extractable in the future. It includes: economic reserves, marginally economic reserves and sub economic resources.

**Inferred reserve base:** The quantitatively estimated reserves based on geology and knowledge, no real measurements. Continuity beyond the reserve base is assumed for the estimates.

**Reserves:** The part of the reserve base that could be economically extracted or produced at the time being, it is only the recoverable material that is taken into account. It doesn’t signify that extraction facilities are operative or even exists.

**Economic reserves:** The part that can be economically profitable produced or extracted by defined investments has been established, either by analytical methods or by reasonable certainty.

**Marginal reserves:** The part of the resources that is on the border of being economically profitable, the resources that are economically uncertain. Resources that could be economical if technology or economy was improved are also included.

**Sub economic resources:** The part that does not meet the criteria for economic or marginal reserves.

**Undiscovered resources:** Resources believed to exist, separated from identified resources. It can be supposed that there reserves are economic, marginal or sub economic. The undiscovered resources are divided into two parts; hypothetical- and speculative resources.

**Hypothetical resources:** Resources that are not discovered but have similar geological structure and are expected to exist in the same region as already identified resources.

**Speculative resources:** Undiscovered resources that are in either favorable mineral deposits or in deposits that is unrecognized for its economic potential.
Other occurrences: The part that has too low grade and depth to be economical. There is a fine line between sub economic and other occurrences, but other occurrences are usually even lower grade and less favorable deposit types.

![Figure 1 - Major Elements of Mineral-Resource Classification, Excluding Reserve Base and Inferred Reserve Base](image)

**Figure 5**, McKelvey diagram (USGS, 2009c)

### 2.2.3 JORC code

The JORC (Joint Ore Reserves Committee) code is an Australian definition of mineral resources and reserves, which is used in many other countries as well. (Vaughan et al, 2002)

**Mineral resource:** A concentration or occurrence of material of economic interest in the earth’s crust in a form, quality and quantity that there are reasonable prospects for eventual economic extraction. Location, quantity, grade and geological characteristics are continuity are known, estimated or interpreted from geological evidence and knowledge.

**Inferred mineral resource:** The part of a mineral resource which tonnage, grade and mineral content can be estimated with a low level of confidence. It is assumed but not known geological and/or grade continuity. The limited or uncertain information comes from drill holes, trenches, pits, outcrops and workings.

**Indicated Mineral resource:** The part of a mineral resource where tonnage, density, shape, physical characteristics, grade and mineral content can be estimated with a reasonable level of confidence. The information is based on explorations, sampling and testing collected from drill holes, trenches, pits, outcrops and workings. The spacing between the locations is too large to confirm geological or grade continuity, but are close enough for continuity to be assumed.

**Measured mineral resource:** The part of a mineral resource which where tonnage, density, shape, physical characteristics, grade and mineral content can be estimated with a high level of confidence. The
information is based on detailed and reliable explorations, sampling and testing collected from drill holes, trenches, pits, outcrops and workings. The spacing between the locations is close enough to confirm geological or grade continuity.

**Ore reserve:** The economically mineable part of a measured and/or indicated mineral resource. Diluting materials and allowances for losses are accounted for when the material is mined. Appropriate assessments and studies have been done which includes consideration and modification of mining, metallurgical, legal, marketing, environmental, social and governmental factors. The material is economically extractable at the time reported.

**Probable ore reserve:** The economically mineable part of an indicated, sometimes measured, mineral resource. Diluting materials and allowances for losses are accounted for when the material is mined. Appropriate assessments and studies have been done which includes consideration and modification of mining, metallurgical, legal, marketing, environmental, social and governmental factors. The material is economically extractable at the time reported.

**Proven ore reserves:** The economically mineable part of measured reserves. Diluting materials and allowances for losses are accounted for when the material is mined. Appropriate assessments and studies have been done which includes consideration and modification of mining, metallurgical, legal, marketing, environmental, social and governmental factors. The material is economically extractable at the time reported.

### 2.2.4 National instrument 43-101

The national instrument 43-101 follows CIM’s definitions for mineral reserves and resources. The classification a deposit gets depends on level of confidence in geological information, quality and quantity of data, level of economic and technical detail and interpretation of data. This is determined by a “qualified person”, definition of that can be found in (CIM, 2010).

**Mineral resource:** A concentration or occurrence of minerals in/on the earth’s crust in such form and quantity and with such a grade or quality that is has reasonable prospects for economic extraction. Factors such as location, quantity, grade, continuity and geological characteristics are known, estimated or interpreted from knowledge and geological evidence.

**Inferred Mineral resource:** A subset of mineral resource where quantity, grade or quality can be estimated by geological evidence and limited sampling, and can be reasonably assumed but not verified, geological and grade continuity. Limited information and sampling is collected from drill holes, trenches, pits, outcrops and workings. Confidence in the estimate is not enough to apply economical and technical applications.

**Indicated Mineral Resource:** The subset to mineral resource which has sufficient confidence of quantity, grade or quality, density, shape and physical characteristics to apply technical and economical parameters to estimate economic viability of the deposit. The information is detailed and comes from reliable exploration which are spaced closely enough for geological and grade continuity to be assumed with reasonable certainty.
**Measured Mineral resource:** A subset of mineral resource which has well established measurements with high confidence, such as quantity, grade or quality, density, shape and physical characteristics, to appropriate technical and economical parameters to support production and evaluation of the economic viability. The information comes from exploration which is spaced closely enough to confirm both geological and grade continuity.

**Mineral reserve:** Is a subset to measured or indicated mineral resource which is economically mineable which is based on a “feasibility study”, (See CIM, 2010), which demonstrate that extraction is economically justified. The study has to show that extraction is economically justified by having information regarding mining, processing economical and other factors. Losses while mining are also accounted for and facilities do not have to be in place.

**Probable mineral reserve:** Is the part of the indicated and sometimes measured mineral resources that are shown to be economically mineable by a feasibility study. The study has to show that extraction is economically justified by having information regarding mining, processing economical and other factors.

**Proven mineral reserve:** Is the part of measured mineral resources that are economically mineable, based on a feasibility study. The study has to show that extraction is economically justified by having information regarding mining, processing economical and other factors.

---

**Figure 6**, Connection between resources and reserves, (CIM, 2010)
2.2.5 Differences in the definitions

These systems described above are not completely consistent with each other but differ in some aspects, see (Vaughan et al, 2002). The definitions can differ in which words are used and how to interpret specific words into mathematical calculations.

For inferred mineral resources, the JORC code and NI 43-101 have different definitions. Regarding to the JORC code inferred mineral resources are assumed to have geological and/or grade continuity but it is not geologically verified. Regarding to NI 43-101’s definition inferred mineral resources are reasonably assumed but not verified geological and grade continuity. USGS estimate of inferred is based on assumption of continuity on real geological evidence. The JORC code and USGS is only required to confirm geological or grade continuity whereas NI 43-101 have to conform both geological and grade continuity for measured mineral resources.

For indicated mineral resources NI 43-101 states that grade and geological and grade continuity is assumed with reasonable certainty. The JORC code states that the samples are not close enough to verify geological and/or grade continuity but close enough for continuity to be assumed. Regarding to USGS definition continuity can be assumed.

The definitions of reserves are the same for JORC and NI 43-101, both include losses while mining. USGS however does not explicitly state that losses are accounted for in their reserve estimation.

When converting resources into reserves different standards do it differently. NI 43-101 must be based on a feasibility study which demonstrates that economic extraction can be justified. The JORC code must be based on “appropriate assessments” which could include feasibility study demonstrating that at the reporting time extraction could reasonably be justified.

For most minerals there is only one estimate of the reserves which is made by USGS. That is problematic which is discussed by Charles and Crawson (2011), since the estimate is done on historically reported reserves and company reported reserves. Some estimates are based on studies made by the US bureau of mines before 1996. Basically, the numbers are based on collected data and not on actual measurements. Also they show historical estimates of the reserves which have been increasing considerably over the years due to new technological inventions and a higher price.
2.3 Lithium reserves and resources

Chile’s reserves are estimated to 7.5 million tons, China’s to 3.5 million tons, Argentina’s to 850,000 tons and Australia’s to 580,000 tons, the total reserves are 13 million tons according to USGS. The lithium reserves are to a large extent situated in South America, apart from Chile and Argentina who produces lithium Bolivia have a lot of resources. (USGS, 2011a)

![Lithium reserves](image)

**Figure 7**, Lithium reserves (USGS, 2011a)

Before 2007, USGS did not report any information regarding the reserves and resources of lithium from China, Argentina, Russia and Portugal (Abell, 2008). USGS estimated the resources to 13 million tons in 2009, a number which had been constant since 1996, 23 million tons in 2010 and 33 million tons in 2011. From 2009 to 2010 China’s and United States’ resources increased by some million tons, also Brazil, Congo and Serbia’s resources are estimated to 1 million tons each. The reserves for the U.S have remained constant. USGS estimated the reserves to 4 million tons of lithium in 2009 and to 13 million tons in 2011 (USGS, 2011a). The amount of resources does not tell anything regarding the actual economic recoverable amount, the reserves. One example is USGS’s presented numbers of both reserves and reserve base for lithium. However after 2009 the reserve base is no longer included in the mineral commodity report, in 2009 the reserve base for Brazil was 910,000 tons and the reserves 190,000 tons, and in 2011 the reserves are estimated to 64,000 tons (USGS, 2011a). Another example of a change in the estimations of resources and reserves are the Greenbushes’, Australia recently re-estimated their proven and probable lithium reserves by 157 % to 31.4 million tons at a grade of 3.1 %. The estimate is based on NI 43-101 (Talison lithium, 2011a.)

As seen in table 1, there are different estimations of resources and reserves. Parts of the difference could potentially be explained by different reporting definitions. Tahil (2008) assumes that the material costs will remain at the same level whereas Evans assumes that there will be a price increase which would impose that parts of the resources will become reserves (Abell, 2008). Extracting the total amount of reserves in some areas will cause a lot of environmental impact (Gruber et al, 2010). Tahil (2008) is only considering brine and not the minerals nor the sea water. Evans, who is a geologist, is considering brine and minerals, not the sea water or other lakes. The reason to Yaksic and Tilton's high lithium resource estimation is that according to them the resources in Salar de Atacama is 35.7 million tons, whereas most of the others estimate the resources of it to between 5 – 7 million tons. Furthermore the Dead Sea and the Great Salt Lake’s reserves are also included. Yaksic and Tilton (2009) estimates the in-situ resources of lithium to 52.3 million tons for brine and the recoverable reserves are 23.5 million tons, assuming a 45 % recovery rate for brine. If instead a more traditional 33 % recovery rate is applied the brine reserves would be 17.3 million tons. Gruber et al (2010) has a relatively high
estimation of the resources, which includes data from 103 deposits, however not the Dead Sea or the Grand Salt Lake. The main focus were deposits with lithium resources higher than 100 000 tons. Clarke and Harben’s estimation included 61 deposits though not specified (Gruber et al, 2010).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Resources [Mtons]</th>
<th>Reserves [Mtons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS, 1996</td>
<td>13</td>
<td>2.2</td>
</tr>
<tr>
<td>USGS, 2000</td>
<td>13</td>
<td>3.4</td>
</tr>
<tr>
<td>Evans, 2008</td>
<td>29.9</td>
<td></td>
</tr>
<tr>
<td>Tahil, 2008</td>
<td>19.2</td>
<td>4.6</td>
</tr>
<tr>
<td>Clarke and Harben, 2009</td>
<td></td>
<td>39.4</td>
</tr>
<tr>
<td>USGS, 2009a</td>
<td>13</td>
<td>4.1</td>
</tr>
<tr>
<td>Yaksic and Tilton, 2009</td>
<td>64</td>
<td>29.4</td>
</tr>
<tr>
<td>Evans, 2010</td>
<td></td>
<td>34.5</td>
</tr>
<tr>
<td>Gruber, 2010</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>USGS, 2010</td>
<td>23</td>
<td>9.9</td>
</tr>
<tr>
<td>Chemetall, 2011</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>SQM, 2009</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>USGS, 2011</td>
<td>33</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 1, Estimations of the lithium reserves and resources (Gruber et al, 2011)

There is a problem with the estimations of the lithium reserves and resources in brine. The classifications of deposits and resources and reserves are made for ore deposits, typically solid deposits. It is not possible to directly apply it on fluids due to complications with pumping and varying density. Houston et al (2011) describes the problem in detail. The extractable amount from the aquifer is normally around one third unless it is a very exceptional case. It is not certain what will happen to the concentration and density of lithium and other elements in the salars when brine is pumped up and fresh water is added. The resources is controlled by the aquifer porosity and the reserves are controlled by the permeability, Houston et al are also suggesting a change in NI 43-101 to account for these problems. With this in mind the numbers for resources and reserves are even more unsecure.
2.4 Neodymium/REE reserves and resources

Even though the rare earths are relatively abundant they have less tendency to be concentrated in economically extractable deposits. Therefore the world’s supply only comes from a few large sources. Usually the first four REEs; La, Ce, Pr and Nd constitute 80 – 99 % of the total REE content in a deposit, therefore deposits containing HREE, heavy rare earth elements, are desired. (USGS, 2002) The total reserves of rare earth oxides (REO) are estimated to 110 million tons and the distribution of the reserves can be seen in Figure 8. China’s reserves have grown from 27 million tons in 2007 to 55 million tons in 2009. (USGS, 2011b) BGS (2010) estimated the REO reserves to 99 million tons, regarding to USGS definition of reserves. In 2011 the reserves of REOs are estimated to 113.8 million tons, China’s reserves are 50 million tons. (BGS, 2011) The industrial reserves in China are estimated to 52 million tons of REO by Chinese statistics, whereas the industrial reserves in Bayan Obo are estimated to 43.5 million tons, it is not clear what the definition of industrial reserves are (Schuler et al, 2011).

![REO reserves in 2009, (USGS, 2011)](image)

**Table 2**, Estimates of the reserves of REOs in the world

<table>
<thead>
<tr>
<th>Reference</th>
<th>Reserves [M tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS, 1996</td>
<td>100</td>
</tr>
<tr>
<td>USGS, 2000</td>
<td>100</td>
</tr>
<tr>
<td>USGS, 2005</td>
<td>88</td>
</tr>
<tr>
<td>USGS, 2011</td>
<td>110</td>
</tr>
<tr>
<td>BGS, 2010</td>
<td>99</td>
</tr>
<tr>
<td>BGS, 2011</td>
<td>113.8</td>
</tr>
</tbody>
</table>

USGS have an optimistic view of the future resources of the REOs and believes that there are many undiscovered sources. There is a phosphate district in Florida which has large inferred quantities of REO. (USGS, 2011b) According to Chen, (2011), Greenland has REE deposits and aims to have 20 % of the market in the future. Other potentially interesting deposits occur in, Sierra Leone, who has an interesting REE deposit in a diamond and gold mine, Vietnam and Malaysia. (BGS, 2010)
The reserve estimation done by USGS in 2011 was quite different from the one done in 2010. Australia’s reserves were decreased considerably due to other definitions of reserves and resources. China’s reserves have been increased again, which could be due to more and better information.

It is difficult to determine the reserves of Nd$_2$O$_3$, however it is done by Jacobson (2011) by assuming that the reserves of Nd$_2$O$_3$ is 18 % of the REO reserves in most countries except for the US were they were estimated to be 15 %, due to a lower concentration in their largest mine, Mountain Pass. In Table 3 the same assumption has been made with both USGS and BGS’s data.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>0.90</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>Brazil</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>4.90</td>
<td>9.9</td>
<td>9.0</td>
</tr>
<tr>
<td>CIS</td>
<td>3.40</td>
<td>3.42</td>
<td>3.42</td>
</tr>
<tr>
<td>India</td>
<td>0.20</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>Malaysia</td>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>20</td>
<td>1.95</td>
<td>1.95</td>
</tr>
<tr>
<td>Other countries</td>
<td>40</td>
<td>3.96</td>
<td>3.98</td>
</tr>
<tr>
<td>Total</td>
<td>15.40</td>
<td>20.09</td>
<td>19.19</td>
</tr>
</tbody>
</table>

**Table 3,** Neodymium reserves in different countries
3. Geology

3.1 Stellar nucleosynthesis

![Figure 9, Atomic abundance of elements in the solar system (Wikimedia, 2011)](image)

The abundance, mass fraction, of elements has large variations, especially for the lighter elements such as lithium and hydrogen, as seen in figure 9. The atomic abundance curve has an exponential decline to \( A = 100 \) and after that it is approximately constant with some variations. Elements with an even atomic number are more abundant than elements with an uneven number due to a higher binding energy. If there is an even number of protons the stability in the nucleus is increased based on the liquid drop model. There is an increasing complexity with increasing atomic number which creates instability in the nucleus. Stability is the main component in the evolution, the more abundant elements tend to be more stable. This is discussed in detail in Burbidge (1959).

Hydrogen is the simplest element and most abundant element. The other elements evolve from hydrogen. Helium is an immediate product of hydrogen burning and is the second most abundant element. In a star hydrogen is the initial fuel, when it is exhausted, the next element, helium, becomes the fuel. If that is to occur the temperature has to increase. The same process will take place for the lighter elements. Thereafter there are different processes to create heavier elements. At higher temperatures the coulomb barrier can be overcame and a reaction can take place, therefore more stable configurations will form, then heavier nuclei can be formed until iron is reached. Neither temperature nor composition is uniform inside a star.

There are different processes or a combination of processes to produce different elements. It was only the lightest elements, such as lithium, that was formed in the big bang. The heavier elements were formed later inside stars. Lithium is produced by the x-process which actually is more than one process, described in detail in Burbidge (1959). The elements produced by the x-process are all unstable at high temperatures such as inside those in stellar interiors therefore it is probable that the production had to take place in regions with lower density and temperatures. Lithium has unusually low occurrence regarding to its low atomic number, since most of the light elements are relatively abundant. The low abundance is due to that lithium is very reactive, and easily reacts with hydrogen forming helium in
hydrogen burning zones where the temperature is high. However, lithium can exist for a longer time in a helium burning zone, long enough to be transported to the surface from the interior. If the star rotates too rapidly lithium is drawn to the middle by the centripetal force, where it is depleted due to high temperatures. $^6\text{Li}$ has a much larger neutron capture cross section than $^7\text{Li}$, therefore $^7\text{Li}$ is more stable and more common.

Neodymium is mainly produced by the slow process (s-process), (Burbidge, 1959). The s-process consists of neutron capture with emission of gamma radiation. The process takes place on a long timescale ranging from 100 to $10^5$ years per capture, it occurs when the neutron density is low and the temperature intermediate. A stable nucleus captures a neutron and becomes radioactive and then decays to its daughter nucleus, and then the next capture takes place. Stable isotopes are produced in this process. It is a common process for creating elements heavier than iron. The most abundant neodymium isotope, $^{142}\text{Nd}$, has 82 neutrons which is a so called magic number where the neutron capture cross section area drastically decreases due to a very stable configuration of neutrons and protons.

Planets, such as the earth, are formed during the collapse of a nebula into a thin disc of dust and gas. These particles accumulate into local concentrations and forms larger bodies by gravitational attraction of heavier elements. They become denser until they collapse inward by gravity and form proto planets. The amount of elements available in a planet is determined by what was available from the beginning during accumulation. The only material that is added is meteors crashing down onto the planet, which is a very low percentage of the weight of the planet. Since the earth is a finite sphere there is a finite amount of available mineral resources depending on the amount that was accumulated and available in the nebula.

### 3.2 General geology of lithium

#### 3.2.1 Geochemistry of lithium

The concentration of lithium in the earth’s crust is 60 ppm, (parts per million, mg/kg) which makes lithium the 27th most abundant element. There are two natural lithium isotopes, $^6\text{Li}$ (7.42 %) and $^7\text{Li}$ (92.58 %) that occurs in nature. (Fasel and Tran, 2005) The abundance does not say anything about the amount of reserves.

Lithium exists in two commercial forms, brines and minerals. Brine is a salt solution, basically in a form of a dry lake. Brine is mainly found in the Andes or in southwestern China, at high altitude, they could also be found with geothermal deposits and oil fields. (Garrett, 2004) About 76 % of the production comes from brines and the rest from minerals. Potentially lithium could also be extracted from seawater and clay (Yaksic and Tilton, 2009). The minerals are found to the largest extent in Australia and in smaller amounts in China, Russia, India and the United States.

There are about 145 minerals containing lithium as a major component, however only a few of them are commercially interesting. There are five minerals in particular that are used for mining lithium: spodumene, LiAlSi$_2$O$_6$, lepidolite, KLi$_2$Al(Si$_4$O$_{10}$)(OH)$_2$, petalite, LiAlSi$_2$O$_{10}$, amblygonite, (Li,Na)Al(PO$_4$)(F,OH), and eucryptite, LiAlSiO$_4$. Spodumene is by far the most common. All of these minerals occur in unusual pegmatite compositions, often together (Garrett, 2004).

Since lithium is an alkali metal it might be expected that it behaves just as the other alkali metals, but it does not. It has a much smaller ionic radius which is the main factor regarding crystallization. Lithium has a similar behavior as magnesium, whose ionic size is nearly identical to lithium, and can be can be substituted into magnesium minerals. It is difficult to separate lithium from
magnesium, therefore the magnesium lithium ratio (Mg/Li ratio) is important to know (Mason, 1959, Tarbuck, 1996).

\[
\text{Mg/Li ratio} = \frac{\text{Number of magnesium ions}}{\text{Number of lithium ions}} \quad \text{[Eq 1]}
\]

In late formed rocks and minerals the ratio is lower due to the properties lithium has. A large amount of lithium is liquid until late stages of crystallization and when magnesium is absent it forms different individual minerals. Magnesium has a higher melting point than lithium and therefore crystallizes earlier. When about 50% of the magma has solidified both iron and magnesium will be depleted from the melt, and then the melt will have a higher concentration of other elements such as sodium, potassium and aluminum (Mason, 1959, Tarbuck, 1996). Minerals that crystallize at the same time will be at the same place.

### 3.2.2 Minerals

Firstly, it is important to understand the granite forming process since most of the pegmatite is located within igneous, i.e. magmatic, rocks as dikes or veins (Tarbuck, 1996). Granite is the last magma to crystallize and pegmatite is usually found in connection to granite. Pegmatite usually consists of the same basic minerals as granite; quartz, feldspar and mica. The main difference to granite is the texture; pegmatite has much larger grains than granite due to a slow crystallization process. Some of the largest crystals ever found were found in pegmatite (Mason, 1959). The crystals are large due to a high water content which makes the crystals grow fast. However London (2005) raises another opinion to the problem, that the cooling process is so fast that the crystallization cannot keep pace with it and therefore there are large grains.

Over 90% of the pegmatite consists of only quartz and feldspar thus are not interesting. The remaining parts of the pegmatite are complex and contain elements such as lithium, beryllium, yttrium, rare earths, niobium, tantalum, thorium and uranium. Different pegmatite consists of different elements and it is not yet understood why that is except for the difference in the origin of the magma (Mason, 1959).

Pegmatite is an intrusive igneous rock which is build up by a range of different minerals. An intrusive rock is a rock that has been formed and cooled below the surface of the earth and an igneous rock is formed by magma that has crystallized and then solidified. It is often found as irregular dikes, lenses and veins. It is more complex than ordinary granite rocks. The form of pegmatite can be seen in figure 10 (London, 2005).

Pegmatite is the result of the last magma, the residual fraction of silicic melt that has been pushed up into fractures of already existing granite crystallized rocks which enlarges the fractures (Garrett, 2004). The silicic melt is unusually fluid due to an increased amount of water and different elements. These elements act as a driving force to inject the melt along weak surfaces of the surrounding rocks (Mason, 1959). Because of its solubility and low melting point lithium is one of the last elements to crystallize and therefore it is found in larger concentrations in areas that were the last to crystallize. These areas can contain other elements such as boron, rare earths and uranium that have not been crystallized at first because the concentration was too low (Garrett, 2004).

Pegmatite can occur in different forms. Either they are in principal homogenous since the changes in the rock are very small, or the rock is split into different areas, i.e. zones. The complex
pegmatite is often internally zoned and thus contains a specific rare mineral at a certain zone, there can be up to 6 different lithium mineral zones (Garrett, 2004).

Most of the lithium rich pegmatite has similar a composition, they contain more feldspar than quartz. The minerals spodumene and petalite are constituted of the same elements, but nor formed under the same circumstances. Petalite forms if the melt reaches the field boundary at high temperatures and low pressure, spodumene are instead formed at lower temperatures and higher pressures. Eucrytite is formed differently probably in presence of gases (Stewart, 1978).

### 3.2.3 Veins

Some important vein deposits are formed by hydrothermal (hot-water) solutions. The origin is thought to originate from hot fluids with high metal concentration that are the rest of the late stage magmatic process. Solidification of the metals and fluid is taking place near the top of a magma chamber, since these solutions have a high mobility they can migrate long distances before being deposited. Parts of the fluid moves along the fractures where it cools off and then metals are deposited in i.e. vein deposit (Tarbuck, 1996).

![Figure 10, Formation of veins and pegmatite (Adapted from UCIrvine, 2011).](image)

### 3.2.4 Brine

The main source of lithium is brine. High concentration brines are mainly found in high altitude places, like the Andes and south-western China, Tibet. These places are volcanically active and the brine was formed by highly concentrated lithium geo-thermal springs flowing into closed areas. The salts became more concentrated due to evaporation and deposition which took place over a long period of time. Since the lithium salts are highly soluble they were among the last salts to crystallize. Some elements and salts in the geo-thermal springs were absorbed into clays and rocks, however lithium remained soluble and therefore high concentration brines could be formed (Garrett, 2004).

A small part of the lithium in the brine could come from surface leaching of volcanic ash, clays or other rocks by water. The water has to be very hot to be able to leach lithium from rock lattices. The
temperature has to be in the range of 275 – 600°C for 0.24 – 2.4 ppm to be dissolved. This means that most of the lithium probably came from the geo-thermal waters and not from leaching since commercial brines has concentration at around 1000 ppm (Garrett, 2004). One of the main economic aspects of brine is the magnesium lithium ratio, see equation 1. If this ratio is too high it might not be economically possible to extract lithium from the brine due to increased extraction costs of separating magnesium and lithium.

The structure of the brine is important, since it determines which part is economically extractable. The bottom of the salt lake consists of a solid deposit called halite or rock salts, which are dried out salts that are solid and impermeable. The middle layer is porous and therefore permeable. The liquid brine can flow through the layer. The useful brine is the liquid layer that can flow quite through the permeable body. On top of the liquid layer there is a thin salt crust which can sometimes be flooded with water (Tahil, 2008).

### 3.2.5 Seawater

Seawater could potentially be a lithium source in the future. The average concentration of lithium in seawater is 0.17 ppm (Fasel and Tran, 2005). There is a variation in the lithium content in the sea water. The concentration in the Dead Sea is considerably higher at 10 ppm and the grand salt lake, Utah, USA, has an average concentration of 400 ppm (Tahil, 2007). There is a very large amount of seawater, therefore there are large theoretical resources of lithium even though the concentration is very low, and the calculated theoretical resources are 2.3 x 10^{11} tons (Fasel and Tran, 2005). The resources reported by USGS are 33 million tons, which would be 0.00014% of the theoretical saltwater resources. There is research on extracting lithium from seawater, but no current economic commercial technology.

### 3.3 General geology of neodymium

#### 3.3.1 Geochemistry

In the earth’s crust the concentrations of some REEs are: Cerium 60 ppm, Yttrium 33 ppm, Lanthanum 30 ppm and neodymium is 28 ppm. Copper’s average concentration is the earth’s crust is 50 ppm. The least abundant REE are still more abundant than for example cadmium, though the concentration of the elements varies considerably (USGS, 2009b).

REE mainly occur as oxides in nature. The oxides are mainly found in three minerals; bastnäsite, monazite and xenotime. Bastnäsite was first discovered in Bastnäs, Sweden, in 1838 by Wilhelm Hisinger, thereafter more elements such as cerium and lanthanum were discovered in the minerals. Bastnäsite and monazite are the primary sources for LREEs (light rare earth elements), xenotime is mainly a source of Y and HREEs (heavy rare earth elements). Monazite contains more radioactive thorium than bastnäsite thus bastnäsite is the main source of LREE. Neodymium is a light rare earth element thus the focus will be on the minerals bastnäsite and monazite (BGS, 2010, Kanazawa and Kamitani, 2006).

The REEs have similar nature and often substitutes each other in different crystal structures. Materials have impurities and vacancies in the lattices and atoms can substitute each other in lattices if they have the same size and oxidation state, or as long as the total charge is the same. That is the reason that there are many REEs in a single mineral and a broad overall distribution. The abundance of the different rare earth elements varies considerably, due to two main reasons. REE with even atomic
numbers are more abundant than odd numbered REEs. Furthermore the lighter REEs have a higher concentration in the earth’s crust due to that they are more incompatible than the HREEs (BGS, 2010). Neodymium is a LREE and has atomic number 60 and are therefore quite abundant compared to other REEs.

The ionic radii of LREEs are slightly different from HREEs which affects the crystal structure and/or the coordination number, the number of nearest neighbors. The LREEs have a coordination number, between 7 – 11, most of them in the range of 8-10 whereas the HREEs have a coordination number of 6-8, but predominantly nr 8. LREEs mainly occur in carbonates, such as bastnäsite, and phosphors such as monazite. HREE mainly occurs in oxides which are less common sources for REE’s. Both LREE and HREE occur in phosphates, which have coordination number 8 – 9, however LREE is more common. Silicates can have a range of the different coordination numbers, therefore both LREE and HREE occur in silicates (Kanazawa and Kamitani, 2006).

The REEs concentration is increased by substituting other ions with similar ionic radius in the rock forming process (BGS, 2010). The ionic radius of REE are similar to those of Na+, Ca2+, Th4+, U4+. Therefore it is common they change places (Kanazawa and Kamitani, 2006). The REEs have a large radius and a low concentration, thus it is difficult for them to replace other ions in magmatic crystallization and create an economical concentration. In pegmatite, the concentrations of REEs are low, but they do replace Ca2+ in the specific mineral structures (Mason, 1959).

### 3.3.2 Minerals

Neodymium is most commonly found in the minerals bastnäsite (Ce,La)(CO₃)F and monazite, (Ce,La,Y,Th)PO₄. These minerals are mainly mined in China, USA, India, Australia and Brazil. The rare earth oxide (REO) concentration in bastnäsite is approximately 75 %, in monazite the concentration is about 65 % (BGS, 2010). Bastnäsite accounts for about 80 – 90 % of the total rare earth mineral (REM) production in the modern society (Naumov, 2008).

REE deposits are found in different rocks. The concentration depends on the rock forming processes and the mineralogy. Furthermore it also depends on enrichment in magmatic and hydrothermal fluids, separation into mineral phases and precipitation. In a later stage weathering and other surface processes also have an impact on the concentration. There are two different categories of REE, primary deposits and secondary deposits. Primary deposits are the main source, they are created by magmatic processes, and can be carbonatites or alkaline deposits. Secondary deposits are concentrated by sedimentary processes and weathering. They are mainly placer deposits and residual weathering deposits (BGS, 2010).

Carbonatite rocks are a kind of igneous rock that contains more than 50 % carbonate minerals. The rocks are mainly found in specific regions such as Brazil, eastern Canada, Russia, East Africa and northern Scandinavia. The rocks originate from magma from the upper mantle which was carbon dioxide rich and silica poor. These rocks are found together with alkaline igneous provinces and usually occur in old stable parts of the continental plate that experienced faulting, large – scale rift structures. The forms of these rocks are as dykes or sills in alkali complexes, also as irregular masses which does not necessarily have to be in connection to alkali rocks. These rocks are enriched in certain elements such as calcium, magnesium, REEs etc. Both bastnäsite and monazite occur in carbonatites. These minerals developed in the later stage of carbonatite forming which makes it difficult to know whether these came from the magma or hydrothermal fluids (BGS, 2010).

In carbonatites it is rare that the REEs are concentrated by primary crystallization, but sometimes it gives an economic deposit. The REEs that crystallizes are concentrated into two different
minerals, apatite and calcite. After cooling for a while calcite is replaced by other minerals and then releases REE. The REE’s are then incorporated into monazite and bastnäsite and also other minerals as they are crystallizing from fluids. In carbonatites, REE minerals are situated in veins where bastnäsite concentration is typically around 10 – 15 %. Otherwise deposits with REE are associated with late stages vein and replacement mineralization, both within carbonatites and other surrounding rocks. The fluid thereby come from carbonatites or processes such as weathering. Hydrothermal mineralization of REEs usually takes the form of fracture filling. Low temperature fluids can break down primary minerals and therefore release REEs and then secondary REE minerals can form (BGS, 2010).

Peralkaline rocks have a high concentration of alkaline metals such as sodium and potassium. If the concentrations of these elements, potassium and sodium are higher than the aluminum concentration the rock is defined as peralkaline. These rocks are characterized by enrichment in alkali metals and titanium, niobium, zircon and REEs. The REEs have relatively low concentration but are enriched in HREEs and yttrium. The mineralization process is not completely understood and different for each deposit. It is, however, known that the initial enrichment comes from magmatic processes. The concentration of REEs in magmas are probably increased by crystal fractionating and vapor-phase transport. Some deposits are completely enriched by magmatic processes in others further enrichment comes from hydrothermal processes (BGS, 2010). The increased concentration is also due to metasomatic processes, where one element is exchanged for another in a certain mineral. For all of these processes to take place it is important that fluorine is present to lower the viscosity, which helps transport of REEs. Kvarnefjord, Greenland, seems to be enriched due to remobilization of REE’s by volatile-rich fluids (Richardson, 1996).

### 3.3.3 Placer deposit

A placer deposit is concentrations of minerals that have been transported and deposited together with sand and gravel by rivers and coastal processes. Originally the elements come from different sources, such as minerals enriched in titanium, zircon and REE. Monazite is the most important REE bearing mineral in these deposits. The main deposits are those close to the shorelines. Minerals have been concentrated by tides, waves and currents. In these deposits monazite is a minor constituent, less than 0.1%, therefore production of REE from sands is only economical when mined as a byproduct to other minerals. India has a lot of placer deposits where the monazite concentration is 1 – 2 %. The placer deposit resources India has are estimated to 2.7 million tons of REO. Australia has placer deposits where the reserves are estimated to consisting of 580 000 tons of monazite, and 170 000 tons of xenotime. Brazil have deposits of 48 000 tons (BGS, 2010).

Monazite is a phosphorus LREE mineral that also contains large amounts of thorium and uranium. The mineral has a high density and therefore concentrates in beach sands, placer deposits, when it is weathered from pegmatite. Most of the world’s thorium resources/reserves occur in beach sands. In the early mining history of REE, before 1980, monazite was the main source. Because of its radioactivity other sources are preferred nowadays, since there are more environmental restrictions. (BGS, 2010)

### 3.3.4 Residual weathering deposits

Laterite is a surface deposit formed by tropical weathering of rock forming minerals and leaching of soluble elements among them calcium and magnesium. Aluminium and iron are enriched due to their insolubility. In certain conditions when the weathered rock is for example a REE enriched carbonatite, REE is released during the weathering and can form new minerals such as monazite. The deposits
formed this way are high grade, the monazite concentration can be 10 – 25 %. Mount Weld, Australia, is a residual weathering deposit. If the rock is unweathered the REO content is 0.1 – 0.2 %, by leaching and redepositing of groundwater under a long period of time the concentration can be enriched to 40 % REO. (BGS, 2010)

3.3.5 Ion-adsorption clay
Ion adsorption clays are a quite newly discovered deposit of REEs. These deposits are to a large extent found in southern China. Xunwu, Jiangxi province, is an ion adsorption clay where the neodymium concentration is 31.7 % of the REO concentration (USGS, 2002). The deposits are associated with weathered granites enriched in REEs. The weathered released REEs are absorbed by clay minerals. The layer of REEs in the clay range from 3 to 10 meters, the most enriched REEs are at about 5-10 meters depth. The REE concentration is relatively low, about 0.05 - 0.2 %, and the HREE concentration is 0.002 – 0.05 %. The concentrations of radioactive elements are also low (Kanazawa and Kamitani, 2006).

3.3.6 Deep sea mud
Deep-sea mud contains considerable amounts of REE regarding to drillings on the sea-floor, on a depth of 4 000 – 5 000 meters. The main REE sites are in Eastern South Pacific and the Central North Pacific. The mud is enriched in HREE, the concentrations are higher than in ion adsorption clays which is the main current source of HREE. The concentration is 1000 – 2230 ppm of REE, 200 - 430 ppm of HREE and both uranium and thorium are almost depleted. The mud layer on the sea floor is about 3 – 10 meters thick depending on the site. The resources on the sea-floor could exceed the reserves on land, which according to Kato et al (2011), are 110 million tons of REO. The drilling sites are not spaced closely enough to properly statistically determine the resources. The local currents, variable sedimentation and irregular bottom topography can create large variation on a short distance.
4. Mining and production

To be able to extract the actual elements or compounds demanded there are many processes involved. The first is to locate where the minerals are and if it is an economically minable deposit. Then the ore has to be extracted by either surface or underground mining. Thereafter different extraction processes are performed to differentiate the elements in the mined ore until the wanted elements or compounds are retrieved. There are several processes included for retrieving specific elements since the minerals they are found in are complex. The main mineral mining method is surface mining about 60 – 70 % of all mines are open-pit mines. Hard rock deposits, such as pegmatite deposits, are extracted by both open pit and underground methods. It is more expensive to open an underground mine therefore the deposit has to have a higher concentration (Encyclopedia Britannica, 2011). The recovery rate is estimated by National Research Council, 1976, and Evans to 75 % for open pit mines and 50 % for underground pegmatite deposits (Gruber et al, 2010).

Even though a mine can have large reserves everything is not commercially minable. The energy cost of mining and refining is given by (Rosa and Rosa, 2008).

\[ J = \frac{C}{gY} \quad \text{[Eq 2]} \]

Where \( J \) is the unit mass of the product, \( C \) is the energy needed to mine, mill and increase the concentration of the product per unit mass, \( Y \) is the joint recovery rate or yield and \( g \) is the mass fraction of the substance in the ore.

This equation gives the extraction limit of a certain substance proportionally dependent on concentration of the substance (Rosa and Rosa, 2008). Therefore if the concentration is decreasing or is lower in a certain mine the energy needed to extract the substance is increasing. If the metal prices are increased enough then it is economical to mine lower concentration ore.

![Figure 11, Mining methods (KGS, 2006)](image-url)
4.1 Surface mining

There are different methods of surface mining: open-pit mining and strip mining. The most common method for lithium and REE are the open-pit- and strip mining. Therefore the focus will be on those two methods. Open-pit mining usually results in a large hole or pit, strip mining usually results in a long narrow strip done by a large shovel or a similar device. Another method is quarrying which is mainly recovering crushed stone, gravel.

When it is no longer economical to extract elements form the mine it has to be closed and then restoration has to take place to ensure land restoration, the water quality and the waste area. Otherwise there could be water pollution, soil erosion and vegetation problems. Plants neutralize and build a solid soil structure and help the area to recover. It is important to plan in advance where to put certain heavy metals or acid producing material otherwise pollution could take place. The information below is from Encyclopedia Britannica, (2011) and more can be read there.

Open-pit mining can take place if there is a deposit near the surface, typically less than 100 meters down. Usually the deposit resembles a converted cone. The first step is to remove some waste rock to reach down to the minerals. Rock breaking is done by blasting and drilling, and the waste material is transported away. The deposit is divided into different horizontal layers, i.e. benches. The height of the bench depends on the deposit, the mined minerals, the equipment and machines used. For large deposits the height of a bench can be about 12 – 15 meters. The top of each bench is a working level, and usually many benches at different elevations are mined simultaneously. To get to different levels a ramp system is needed. To make a new bench firstly the ramp system has to be expanded downwards. This is done until the deposit is not economical anymore. Sometimes a single bench is enough to extract the whole deposit.

The angles of the wall are important for the mine not to collapse and with greater depth it is crucial that they are stable. The angle of the walls are essential, if the angle is increased by a few degrees it can decrease the costs and therefore increase the profit of the mine. However it can also risk the safety of the mine due to slope failures. Depending on the geological conditions various angles can be used in different parts of the mine.

Surface mines are cheaper than underground mines, but when the costs of mining waste rock are too large the production declines (Encyclopedia Britannica, 2011).

Strip mining is used when the deposit is close to the surface. A long strip of soil or rock is removed to uncover the deposit. This is done by the largest in the world, bucket wheeler excavator, that can remove 12,000 m$^3$ waste rock per hour. Either area stripping or contour stripping is used. Area stripping is performed when the terrain is flat and the deposit covers large areas. Contour stripping is done in mountainous terrain when the deposit follows a certain contour in the land and it leaves a terrain that looks like terraces behind. It is mainly used for coal or tar sand (Encyclopedia Britannica, 2011).

4.2 Underground mining

Underground mining methods consist of a range of different methods depending on the rock and wall supporters. There are unsupported, supported and caving methods. The concentration of the mineral has to be higher than in a surface mine due to higher costs for extracting it. Smaller machines have to be used, and the access is limited but the productivity is considerably reduced per worker shift. One advantage is that there is basically no waste rock that has to be mined.

Depending on the concentration, different methods can be used. The more profitable a mine is the more expensive methods can be used. Also depending on how easily separated the waste and
minerals are different methods are used. If it is easy to separate waste and ore less selective methods can be used (Encyclopedia Britannica, 2011).

Longwall mining is another method of mining where a slice is removed from the wall in one instant. The slice is about 1-2 meters thick and can be up to some kilometers long. Hydraulic supporters are placed so that the rock can be mined safely, (see figure 12). A cutting machine moves back and forward under the supporters. The hydraulic supporters are moved forward after mining and the overburden rock is allowed caved in behind. This method can only be used for softer rocks which can be sliced into thin pieces. The recovery rate is better than for pillar and room mining. Another advantage is that there is no blasting and roof support needed. The above ground can sink down a meter or so when the mine is allowed to cave in. (Encyclopedia Britannica, 2011)

![Figure 12, Longwall mining (Wikimedia, 2010)](image)

Room and pillar mining is the most common technique for underground mining. It is a horizontal mining process where pillars are left for roof support. Waste can be used to fill up the space in between the pillars when one area is completed, which forces the air flow in a specific direction where the workers are. This is used as reinforcement for the roof support. About 60% can be recovered with this method, a large part of the rest of the minerals are left in the pillars. The sizes of the pillars are important, too large ones contain too much valuable material, and if they are too small the mine can collapse. (Encyclopedia Britannica, 2011)

![Figure 13, Room and pillar mining (Encyclopedia Britannica, 2012)](image)

4.3 Leaching

Leaching can be an alternative extraction method to traditional rock mining. Different solvents, often acids are injected into the ore body, or used directly on heaps of ore. There are two different sorts of leaching; in situ- or heap leaching.

4.3.1 In-situ leaching (ISL)

In situ-leaching is a mining method for recovering certain elements. Acid solutions are injected on one side of the deposit in an injection well. This liquid solution will react with the ore body and dissolve rare earths and together the fluid and dissolved rare earths will be pumped up through recovery wells on the other side of the deposit. The rock has to be permeable in order for leaching to be effective. Sometimes the rock is fractured either by explosives or hydraulically, to make it permeable. ISL is very cheap
compared to other mining methods. It can be used immediately, without excavation costs. The ground water can be affected by the acids used in in-situ-leaching furthermore heavy or radioactive metals can be dissolved and affect the surrounding nature (Encyclopedia Britannica, 2011).

### 4.3.2 Heap leaching

Heap leaching is performed on ores that have been brought up to the surface for treatment. Usually the concentrations of those ores are not economically interesting without enrichment. The ore is piled up and a leaching solution is sprayed on top of it and collected beneath it. The solution then contains dissolved elements which can be extracted. This method is becoming more common since many ores being mined today have a lower concentration than before, and enrichment is needed before large parts of the ore is commercially interesting. The close environment is at risk while performing heap leaching due to acid solutions therefore the method is not widely used, but mainly performed in countries that have less strict environmental laws it is done. (Encyclopedia Britannica, 2011)

### 4.4 Brine solution mining

Brine solution mining is a mining method for brine, where a borehole is drilled to the top of the salt formation. A steel pipe is extended to the bottom of the formation and outside of the steel pipe is a case. Water is injected between the case and the inner tube and then emerges at the top of the salt formation. The water dissolves the salt and the brine sinks to the bottom and is then pushed up through the inner tube. The brine is stored in tanks. Another method is injecting water at the bottom and then the brine is collected at the top of the salt formation. If two wells can grow together production is increased markedly. A large amount of water is needed to extract the brine which can lead to consequences for the nearby population. The two methods function the same way, the only difference is which geometrical form it leaves behind. A cone if the water is injected from the bottom, otherwise an inverted cone (Encyclopedia Britannica, 2011).

### 4.5 Extraction methods

#### 4.5.1 Flotation

Flotation is a process that separates and concentrates ore by making the surface either hydrophobic or hydrophilic. The minerals need a coating to be able to float, which is done chemically. The main idea is to make some parts of the ore hydrophobic and other parts hydrophilic to separate them. If they are made chemically hydrophobic, they adhere to an air bubble to float to the surface and forms froth. If made hydrophilic they sink to the bottom. With this method the waste minerals can potentially also be concentrated and processed (Encyclopedia Britannica, 2011).

#### 4.5.2 Extraction of lithium from minerals

The most common lithium bearing mineral is spodumene which commercially exists to a large extent in Australia. The extraction process of lithium from spodumene is largely dependent on which end substance is desired. If the lithium concentration is under 3 % firstly it has to be enriched by for example flotation. The first step for extracting lithium from spodumene is to convert it from alpha to beta form by heating it to 1100°C. Lithium in beta form spodumene can be displaced by sodium or hydrogen at
higher temperatures or by pressure leaching. The most common method is to dry mix with sulphuric acid and heating to 250°C to displace the lithium, then dissolve the lithium and further separate and wash it. To further purify the lithium, iron, calcium and magnesium are precipitated by sodium hydroxide. The remaining solution is treated with sodium carbonate, which precipitates lithium carbonate. Then it is washed to remove the sodium and lastly dried then containing only lithium carbonate (Bale et al., 1989).

### 4.5.3 Extraction of lithium from brines

After brine solution mining, the brine is stored in tanks, and then it is pumped to a solar evaporation pond to remove water and crystallize the present salts. A solar evaporation pond is an artificial pond made for natural evaporation of brine. After some time in a pond sodium chloride is produced and removed. Then the rest is moved to another pond and further evaporated. The final process is to remove boron, sulphate and magnesium to purify the lithium salts. Then the product is lithium chloride, to produce lithium carbonate more processing is needed. To be able to commercially produce lithium by solar evaporation the conditions of the site have to be very specific; low humidity, high evaporation rate and low average rainfall. The commercial brines are all situated at a high elevation where the humidity is relatively low, and in dry places where evaporation rate is high. The evaporation rate determines how large the evaporation pond has to be. With a higher evaporation rate the pond can be made smaller (Garrett, 2004). If the Mg / Li ratio is too high then LiCl will not be crystallized in the evaporation ponds. This has been a problem in some areas however if the brine is treated with calcium hydroxide then the magnesium content will decrease and extraction can take place (Tahil, 2008). The recovery rate for brines varies from 33% (Houston et al., 2011), 45% (Tahil, 2007) to 50% (Gruber et al., 2010). The rest of the brine that is not recovered is injected back into the salt lake.

### 4.5.4 Extraction of lithium from seawater

There are some major problems with extracting lithium from seawater; a process factory has to be built close to the ocean to extract the lithium. That demands certain conditions, not too much wind, not too hot and without flooding problems. There are other byproducts in water need to be purified and commercialized. The magnesium lithium ratio is very high, which makes the extracting process more difficult. A small scale Japanese experiment got 750 g lithium metal from processing 4200 m³ water. Recovery efficiency was then 19.7 % (Fasel and Tran, 2005). There is research regarding other projects and methods for recovering lithium from saltwater. Currently there are no commercial possible methods available.

To illustrate this with an example, if a facility were to produce 2000 tons of lithium annually, it would be 8 % of the current lithium production of 25 000 tons. That is a reasonable size of a facility. How much water needs to be processed for producing 2000 tons expressed in m³/s? If the recovery rate is 30 % or 100% resectably and the concentration is 0.17 ppm, 10 ppm and 400 ppm. 

\[
V = \text{numbers of kg/year } / (\text{concentration } \ast \text{ recovery rate } \ast \text{number of seconds in a year})\]  

\[\text{[Eq 3]}\]

If the concentration is 0.17 ppm, 0.17 mg/m³, the amount of water that needs to be processed is 1244 m³/s, if the lithium concentration is 10 ppm, then 21 m³/s water needs to be processed. The mean water flow, in the largest river in Sweden, Lulea älv, is 498 m³/s. If this number were converted to barrels/day, one barrel is 159 liters, for seawater it would require 676*10⁶ barrels/day to be processed. The Dead Sea would need to process 11.4*10⁶ barrels/day. The largest oil refinery in the world, Jamnagar refinery, India, produces 1.3*10⁶ barrels/day. The amount of water in the Dead Sea is 1.47*10¹¹ m³ and the
amount that needs to be processed in one day is $1.81 \times 10^6 \text{ m}^3$ and in a year $6.67 \times 10^8 \text{ m}^3$ of water, which is 4.5\% of the water in the Dead Sea.

<table>
<thead>
<tr>
<th>Lake/Sea</th>
<th>Lithium concentration [ppm]</th>
<th>Recovery rate 30 % [m^3 water/s]</th>
<th>Recovery rate 30 % Barrels/day</th>
<th>Recovery rate 100 % [m^3 water/s]</th>
<th>Recovery rate 100 % Barrels/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Salt Lake</td>
<td>400</td>
<td>5.28E-01</td>
<td>2.87E+05</td>
<td>1.59E-01</td>
<td>8.62E+04</td>
</tr>
<tr>
<td>Seawater</td>
<td>0.17</td>
<td>1.24E+03</td>
<td>6.76E+08</td>
<td>3.73E+02</td>
<td>2.03E+08</td>
</tr>
<tr>
<td>Dead sea</td>
<td>10</td>
<td>2.11E+01</td>
<td>1.15E+07</td>
<td>6.34E+00</td>
<td>3.45E+06</td>
</tr>
</tbody>
</table>

**Table 4, Amount of water for processing lithium from seawater**

### 4.5.5 Extracting and separation process of REE

Processing the REE’s is the next step after mining, it usually takes place close to the mine. The elements need to be separated and concentrated, which is done by using chemical and physical processes such as heap leaching. Firstly the ore has to be crushed into smaller pieces, about gravel size, then grinded into fine sand. After that the bastnäsite is singled out and elements have to be separated which is done by different chemical processes depending on the compounds and elements. The REEs are often processed into oxides. As such they are stored, shipped or further processed (BGS, 2010).

Separations of REE’s are difficult due to their similar chemical properties. Most of the REE’s are separated by solvent extraction and ion exchange. Solvent extraction (SX) is the best method for separating LREE. SX separates the elements due to their relative solubility in two mixable liquids, usually water and an organic solvent. For this process to function the REE’s have to have different solubility in the liquid phase used in these solvents. The process is repeated several times to acquire a good result. The end products are solid rare earth salts or oxides to a purity of more than 99.99\% (BGS, 2010).

China can produce the purest REE’s since they have the most advanced processing methods. Separation is a costly process. A large scale separation unit only exists in China today since the cost to set up a new one is around 500 million dollars (Nickels, 2010).

There are also other deposits in southern China such as ion adsorption clays, where the concentration is lower. However, processing is easier due to small depths, drilling and blasting is not necessary (BGS, 2010). Before heap leaching was used, but now it is banned due to environmental risks instead in situ leaching is used (Schuler et al, 2011). Since the energy input for extracting the REE is low from ion adsorption clays, the REE concentration can be reduced, equation (3) (Kanazawa and Kamitani, 2006, Naumov, 2008).
5. Historic production

5.1 Lithium mines

The main pegmatite sources are located in the US and in Australia. Other pegmatite sources are located in Canada, China, Russia, USA, Zimbabwe and Zaire. However those deposits are less than 3 % of the total current production and are therefore not detailed here. In the future they are possible producers of lithium (Gruber et al, 2010). Recently there are large deposits found in Afghanistan and they could contain large amounts of lithium. There are both pegmatite and brine found however due to bad infrastructure and wars there has not been a really good study regarding how much is actually available in the deposits (Afghanistan Geological Survey, 2011).

5.1.1 Greenbushes

The Greenbushes, Australia has a large spodumene deposit which consists of an average concentration of 3.9 % Li$_2$O. The reserves were estimated to 7 million tons of lithium. In 2011 the mining company, Talison estimated their proven and probable resources to 31.4 million tons of 3.1 % Li$_2$O. The production from the Greenbushes is 60 % of Australia’s total lithium production, or 19.8 % of the world’s lithium production (Talison Lithium, 2011a). Apart from lithium the Greenbushes is also the main producer of the metal tantalum (Bale et al, 1989.) The lithium concentration is 1.59 % (Gruber et al, 2010). The lithium is found in veins that are about 250 meters thick (Fasel and Tran, 2005).

Both open-pit and underground methods are used to mine lithium in Greenbushes, Australia. Different methods to enrich the lithium are used, including gravity, floating and magnetic processes. Gravity processes separates light unnecessary elements from valuable heavy minerals by their different density in water. The heavy minerals can be found on the bottom and collected from there. Magnetic separation makes different particles fall into different spectrum sizes depending on their magnetic attraction (Talison Lithium, 2011a).

5.1.2 Kings Mountain

The deposit Kings Mountain, North Carolina, USA, is the largest spodumene deposit in the US. It has the largest in-situ lithium pegmatite resources in the world (Gruber et al, 2010). It makes up 80 % of the reserves in the U.S. The lithium grade is 0.69 % (Yaksic and Tilton, 2009). However it is not currently under operation. There were two mines in the deposit, both were mined with open-pit techniques, one was closed in 1986 and the other in 1998 (Tahil, 2008).

5.2 Lithium Brine

Since most of the lithium production comes from brines, the same method, brine solution mining is used. The conditions, lithium concentration and magnesium lithium ratio differs, why the processes are various costly. The reserves and resources varies considerably depending on the reference. Also, the average concentration varies which makes it difficult to accurately estimate the available amount of lithium in brine. Most of the brine is situated in South America, where the word for salt is salar.

5.2.1 Salar de Atacama

Salar de Atacama, Chile, is the world’s largest lithium brine deposit. Its main product is potassium chloride and lithium is just a byproduct. It also has commercial amounts of boron and sulphate. The
resources are estimated to 6.9 million tons of Li₂CO₃ by SQM, to 3 million tons by USGS (Naumov, 2010, SGU, 2009). The lithium concentration is not homogenou in the salt lake but varies considerably. The average lithium concentration seems to be around 1000 -1500 ppm, where the concentration might reach over 3000 ppm in the central parts of the salar. The central area is 30 km² and the depth is 35 meters (SGU, 2009). The production capacity is 30 000 tons/year of Li₂CO₃ (Garrett, 2004, Naumov, 2010). The magnesium lithium ratio is 6.4 and the lithium grade is 0.15 % (Yaksic and Tilton, 2009). Salar de Atacama is at an elevation of 2300 m and the area is 3000 km². It is one of the driest places on the earth, and therefore has a high evaporation rate (Garrett, 2004). SQM plans to increase the production which demands that other parts of the Salar are put into production, parts which have a lower lithium concentration (SGU, 2009). The lithium extraction is Salar de Atacama consumes about 65 % of the fresh water in the region. About 30 meters down there is solid rock, also containing lithium, and then the lithium cannot be extracted (Tahil, 2007). There are other opinions (Evans, 2008) regarding how far down it is possible to extract lithium.

5.2.2 Salar de Hombre Muerto
Salar de Hombre Muerto, Argentina, is another large lithium brine producer. Total resources are 800 000 tons Li and its lithium content varies between about 200 – 1000 ppm and the average is 521 ppm (Yaksic and Tilton, 2009, Gruber et al, 2010). In large parts the concentration is over 700 ppm. The magnesium lithium ratio is 1.37 (Garrett, 2004, Naumov, 2010). The output is 12 000 tons/year of Li₂CO₃ and 5000 – 7000 tons/year of LiCl. The lake is considerably smaller than Salar de Atacama, only 565 km² and its location is fairly remote and it is situated at an elevation of 4300 m. The Salar is quite small, however lithium can be extracted from greater depths than in other Salars (SGU, 2009).

5.2.3 Salar de Rincon
Salar de Rincon, Argentina, is another salt lake that has just been taken into production, as late as 2007. The reserves are estimated to 250 000 tons by two independent sources. The resources are estimated to 1.82 million tons (Yaksic and Tilton, 2009). Other sources estimate it to 1.4 million tons (SGU, 2009).

5.2.4 Salar de Uyuni
Salar du Uyuni is the world’s largest brine and is situated in Bolivia. It has a large part of the lithium resources in the world. However, this is debated, the estimations range from 6.9 million tons to 3 million tons (Tahil, 2008.) The area of the brine is 9000 – 10 000 km², but the areas where the concentration is over 3000 ppm is about 50 km², with a small area of 280 km² where the concentration is about 4700 ppm. The rest of the lake has an average concentration of about 500 – 600 ppm (SGU, 2009). The brine has high magnesium lithium ratio, 18.6, about three times as high as in Salar de Atacama, which complicates the extraction process. The lithium grade is 0.04 % (Yaksic and Tilton, 2009, Gruber et al, 2010).

5.2.5 Silver Peak
Silver Peak, NV, US has produced lithium since 1966, the lithium concentration has in that time decreased from 360 to 230 ppm. In 1992 the reserves were estimated to 118 000 tons in the lake which is small, only 50 km². The production is around 9000 tons / year, but is declining (SGU, 2009). The magnesium lithium ratio is 1.5 (Yaksic and Tilton, 2009). According to Naumov (2010) the resources are 40 000 tons, however USGS (2011a) estimates the reserves to 38 000 tons.
5.2.6 Brine in China

There are some regions in China with many saltine lakes. The regions are; Inner Mongolia, Tibet salt lakes, Qinghai salt lake area and the Xiangjiang area.

Zabuye salt lake, Tibetan plateau, began producing 5000 tons of Li$_2$CO$_3$ / year in 2005. The lake is situated in an area with another 352 salt lakes. The production rate is estimated to be 20 000 tons/year. The resources are estimated to over 1 000 000 tons (Tahil, 2008). The location of the lake is fairly remote and it is situated at an elevation of 4400 meters. Li$_2$CO$_3$ is found in crystal form (SGU, 2009). The magnesium lithium ratio is 0.001 and the lithium grade is 0.05 – 0.1 % (Tahil, 2008, Naumov, 2010, Yaksic and Tilton, 2009).

Qaidam Basin, Qinghai Province, is an area in China which has about 33 salt lakes and playas. The lithium resources are 2.02 million tons (Yaksic and Tilton, 2009, Gruber et al, 2010). The magnesium lithium ratio is high but due to new improved technology it is possible to produce lithium. The production mainly comes from one lake, Taijiner, apart from producing lithium, Qaidam Basin is currently the largest producer of potash. Lithium production from Taijiner started in 2004 with 500 tons Li$_2$CO$_3$ / year but is currently being expanded, with a processing plant with a capacity of producing 35 000 tons of Li$_2$CO$_3$ / year (Comer, 1977, SGU, 2009).

DXC salt lake is the third salt lake in Tibet, China, which has an Mg/Li ratio of 0.22. The lake is small, the reserves are estimated to 1 tons of lithium chloride, 160 000 tons lithium. It is estimated that the total Li$_2$CO$_3$ production will be 400 000 tons. The area is very remote, 600 km from the nearest railway and at an elevation of 4400 meters (Yaksic and Tilton, 2009).

5.3 Neodymium mines

Rarely are REEs the primary product of a mine. The only mine where REEs are the primary product are Mountain Pass, California. Originally REEs were a byproduct also in Bayan Obo, China, to iron extraction. In Canada REEs were a byproduct to uranium. Brazil have monazite sands which were operated mainly for thorium, but with REEs as a byproduct (BGS, 2010).

5.3.1 Bayan Obo

Bayan Obo, China, is the largest currently existing REE deposit. Bayan Obo was discovered in 1927 and started the production of rare earths in 1957 (Tse, 2011). The main product from the mine is iron. The iron reserves are 1.4 billion tons and the mine also contains 71 other elements, among them niobium (BGS, 2010). It is situated in Inner Mongolia and has estimated reserves of 48 million tons REO (Kanazawa and Kamitani, 2006.) The share of neodymium is 18.5 % as seen in figure 14. (Chen, 2011) There are research about the mineralization process and why the REO grade is so exceptionally high. There are theories such as it is originated from carbonatites which is further discussed in (Castor and Hedrick, 2006) or that an iron ore body first was formed, as discussed in (Kanazawa and Kamitani, 2006).

The REE containing minerals are mainly bastnäsite and monazite. The settings are a 2 km wide ore body which is about 18 km long. It is divided into three zones, the main-, east-, and west-ore body. The REO concentrations differ in the different bodies. The main the average is 6 %, and in the east it is 5 %, the main and east are currently being mined (BGS, 2010, Kanazawa and Kamitani, 2006). The
recovery rate of the minerals increased from 10% before 2005 to 60% after 2005 (Schuler et al, 2011).

Bayan Obo, China, is a surface mine thus open-pit methods are used and it is mined from two open-pits. To separate bastnäsite and monazite from the iron, flotation is used. Different techniques are used to extract the REEs from the minerals. To begin with the mineral concentrate is baked with sulphuric acid at 300 – 600°C and then leached with water, making REE liquid and then precipitate the other elements as waste. The REEs are then also precipitated but as double sulphates, then converted to hydroxides. To purify it further it is leached with hydrochloric acid (BGS, 2010). Originally the REO were produced from iron waste (Castor and Hedrick, 2006).

5.3.2 Mountain Pass

Mountain Pass, CA, USA, is the second largest REE deposit in the world. The deposit originates from carbonatite and is associated with ultra potassic alkaline intrusive rocks. The deposit is similar to carbonatite deposits. However, the iron and phosphor content is unusually low which indicates that the source probably was different than for other carbonatites (Castor and Hedrick, 2006). The main carbonatite body is 1000 meters long, 250 meters wide and consists partly of bastnäsite (Kanazawa and Kamitani, 2006). The REO concentration is 7 % (BGS, 2010). The share of neodymium is 11.2 % (Chen, 2011.) The mine began operation in 1952 and had to close in 2002 due to environmental problems and decreased prices due to increased production from Bayan Obo (Naumov, 2008). The mine is currently undergoing expansion and modernization and is expected to start operating again in 2012. Lots of environmental restrictions had to be fulfilled for the mine to open again. (Schuler et al, 2011)

Mountain Pass, CA is also an open-pit mine. After being mined the material is crushed into 0.1 mm particles. To further concentrate it, the material went through treatments with steam and agents, until the concentration reached 30 -35 %. Then froth flotation was used to further enrich it to 60 %. By leaching with hydrochloric acid the concentration is increased to 70 % because both strontium and calcium carbonates are removed. To further concentrate the REO to 85 – 90 %, calcinations which removes carbon dioxide was used (BSG, 2010).
5.3.3 Mount Weld

Mount Weld, Australia is a residual weathering deposit, and has an exceptionally high REO concentration of 40 % in some areas, but the average concentration is 9.7 % REO. It mainly contains LREE, and the deposit size is 12.24 million tons (BGS, 2010). Naumov (2008) have other numbers of the concentration of 16 – 23 % REO. The share of neodymium is 18.5 %. The extremely high REO concentration is due to extreme enrichment over a long period of time from leaching and re-depositing of REE by the groundwater. The size of the mine, which is an intrusive pipe, is approximately 3 km in diameter (Kanazawa and Kamitani, 2006).

Mount Weld is also an open-pit mine with the main products niobium and tantalum, while REO is a byproduct. After mining the ore it is crushed and grinded into small pieces of 38 µm. Then the REE can be separated from the non REE minerals prior to flotation. After the floatation the REO concentrate is 40 %. Then a thickener is added and solidifying the REE’s into “cakes” which are then taken away to Malaysia to be further processed. The mine will probably start producing REO in 2011-2012 (Lynas Corporation, 2006).
5.3.4 Ion-adsorption clay

Most of China’s production comes from the mine Bayan Obo. Apart from that large extent of China’s reserves are ion adsorption deposits, deposits that contain HREE, the estimation is that these reserves contain 80 % of the total HREE reserves (BGS, 2010). There are two ion adsorption clays in southern China that are interesting; Xunwu, Jiangxi Province, with a neodymium of 30 %, Lognan, Jiangxi Province, with a neodymium concentration of 3 % (USG, 2009b). The production of REO from ion-adsorption clays has increased from 19 500 tons in 2000 to 45 000 tons in 2007 (Schuler et al, 2011).

5.3.5 Other REE mines

Vietnam, Malaysia and Thailand produces REEs, but the current production is small. There are some different mines in Russia but the concentration is relatively low. There are also additional Chinese reserves occur as placer deposits, which are associated with alkaline rocks (Naumov, 2008). There are also pilot projects regarding mines in Greenland, Canada and other places in the U.S (Chen, 2011). There are monazite sands mainly in India and Brazil which contain LREE, but they are currently not being mined due to the large content of radioactive element such as uranium and thorium. If thorium will be mined, REEs could be extracted as a byproduct.

Nolans Bore, Australia, also have reserves of rare earths and plans to open in 2013. The main product is uranium. The REO concentration is 2.8 % and the reserves are 850 000 tons. The neodymium concentration is 21.5 % of the REO concentration. (BGS, 2011)

Kvanefjord, Greenland, is another potential REE mine. There are large resources of REE however it is not yet certain that the mine will produce REE in the future. The deposit would produce both uranium and REEs. The main problems are the environment due to problems with handling the wastewater from mining and the large amount of water coming from snow melting or heavy rain. The water could contaminate the whole system of floods and lakes and finally the ocean with radioactive waste, heavy metals and fluorine. The mine would be an open-pit mine and the uranium would be mined with leaching. The European Environmental Agency (EEA) and Greenland’s government signed a corporation agreement on environmental issues which may make mining possible with exchange of expert knowledge (Schuler et al, 2011).

There are more REO deposits in the world. Recently a large deposit of many elements was found in Afghanistan. However due to political issues and infrastructure the deposit may not be explored just yet. Due to that it is difficult to estimate the actual resources and reserves of the deposit. If a deposit is found far away or in a country which is not politically stable the amount is often overestimated (Montgomery, 2011).

Norra kärr, Sweden, are reported to have REO resources, and are listed as top five REO deposits outside of China (Sullivan, 2011.) Norra Kärr has inferred resources of 60.5 million tons 0.54 % REO, of which HREE is 54 %. LKAB has made a study of their mine in Kiruna which eventually could produce 6 000 tons of REO per year (BGS, 2011).
5.4 Production of lithium

5.4.1 Historic production of lithium

USGS’s data contain gross product of lithium. When comparing the gross product to the lithium metal content with data from both USGS and BGS the amount of lithium metal is only varying between 3% – 8%, and the data from BGS and USGS differs with about 2%. If inserting a trend line, the BGS data shows a decrease in concentration and the USGS data show an increase. The USGS data for lithium metal production is only found from 1994 whereas BGS’s data is ranging from 1974 until today. Brine started to be a large part of the production from 1997, and from 1997 it can be seen in figure 17 that the gross product is rapidly increasing. Also the lithium metal production is increasing however not as much percentagewise as the gross product, giving a negative decline on the trend line for BGS’s data.

![Lithium production 1974 - 2010](image)

**Figure 17**, World production of lithium in both gross product and lithium metal. (USGS, 2011, BGS, 2010)

The gross production figures represent metric tons in gross product lithium minerals and brine. In the late 1990’s brine became the main source of lithium, which can be seen in figure 17 as an increased gross product production. It is also possible to see that even though the gross product has increased the amount of lithium metal has not increased as much, predicting that the concentration is decreasing. The numbers from BGS and USGS differs however the difference is in the range up to 2%, based on different countries being included. In BGS’s number an estimation of the US lithium production is included. Since 1967 lithium production is reported as ore and ore concentrates from mines and lithium carbonate from brine deposits. After 1954 the world production does not include the US. There are no available numbers of their production. Data for 1966-1967 does not include Africa, Zimbabwe was the largest lithium producer at that time, so production was probably considerably higher (USGS, 2010).

During World War Two the specific lithium properties were discovered. Lithium was then used in alkaline batteries in submarines and as a hydrogen source in signaling balloons. After the war new lithium applications were discovered. Lithium were discovered to withstand high temperatures and was
used in ceramics and rocketry. Also greases containing lithium were lubricating at both high and low temperatures. During the cold war in the 1950’s both the Russian and American governments used lithium to produce hydrogen bombs. In the 1960’s it was no longer used for hydrogen bombs and other application were invented. In the beginning of the 1960s lithium was used in air-conditioning and synthetic rubber (Comer, 1977).

The U.S was the main lithium producer between the late 1950 and mid-1980s. In the 1950s the Kings Mountain, NC, began producing lithium from two mines. In 1966 Silver Peak, Nevada, began producing lithium carbonate from brine. When the world production shifted to brine Kings Mountain had to close. Officially both mines were closed in 1998. (Comer, 1977)

Chile began to produce lithium carbonate in 1984, and world production increased, as can be seen in figure 17. Australia doubled their production between 1994 and 1995. In 1995, FMC lithium purchased Salar del Hombre Muerto and perfected and commercialized the purification of lithium chloride from brine with minimal processing. (FMC 2010a) There is a large increase in production from 1997, since SQM (Sociedad química y minera de Chile S.A) entered the lithium market and production from Salar de Atacama increased rapidly (Ebensperger et al, 2005). In 2000 new techniques for developing brines with high magnesium content was discovered and because of that salt lakes in Tibet such as Zabuye and Qaidam region could be processed. In 2003, China began producing lithium from brine. In Australia the lithium production increased from 79 000 tons in 2002 to 124 000 tons in 2003. Argentina increased the production with 50 % between 2003 and 2004 (IOEA, 2011).

Between 1998 and 2004 SQM increased its production capacity from 9000 to 18 000 tons to 28 000 tons Li₂CO₃ per year. Between 2005 and 2006 the price on lithium carbonate was increased due to increased demand and production problems in Salar de Atacama. In 2009 the lithium carbonate price was strongly reduced which reduced the export of lithium carbonate from Salar de Atacama. (PEC, 2011)

Most of the pegmatite deposits had to close due to a reduced price after 1997, though three mines was still in operation. Greenbushes, Australia, Bikita, Zimbabwe and a mine in Canada could keep up their prices because the glass industry need for spodumene concentrate. Small production sites in Canada, Russia and Namibia closed in the late 1990s (PEC, 2011).

Lithium is produced in the U.S, but different estimations exist about how much is actually produced, since the data is not available for the public. Usually it is said that the U.S is among the largest lithium producers in the world. The production is not enough for them to be self-sufficient. BGS mineral statistics reported that the U.S produced 1 500 tons of lithium in 2005, which would be about 8.8 % of the reported world production (BGS, 2010).
5.4.2 Current production of lithium

The lithium metal production in 2010 was estimated to 25 300 tons. About 97 % of the production came from Chile, Australia, China and Argentina. Chile accounted for 34.7 % of the production, Australia for 33.5 %, China for 17.7 % and Argentina for 11.4 %. The U.S has not publically published their lithium production since 1955, however, they import, export and mines lithium. Their reserves are estimated to 38 000 tons (USGS, 2011). The US produced 4 % of the global lithium production in 2007 (Yaksic and Tilton, 2009).

5.3 Production of REE

5.3.1 Historic production of REE

![Figure 19, Historic production of REO (Tse, 2011)](image)

Different mines have been in production at different eras of the REO production. From the beginning REE was produced in small amounts from mainly monazite which can be seen in figure 19, but also in small amounts from pegmatite, carbonatite veins, and as by-products of niobium and uranium extraction.

In the 1940s the Manhattan project started, the U.S wanted to make an atom bomb. Then the fissile material $^{239}$Pu was wanted, which was found together with actinides. The actinides needed to be separated from the plutonium which was done by ion exchange. This was the beginning of the rare earth elements production. It was not until 1950 – 1960 proper techniques for separating REE’s were invented and commercialized and thereafter the industrial usage increased. (Chen, 2011)

In 1965 the REE production increased (see figure 19), due to the increased demand for Europium, (Eu), which could be found in Mountain Pass which then opened. Eu is needed for color TV screens which were commercialized in the 1960s. The increased available amount of REE’s resulted in new applications. Mountain Pass was the dominant REE source until the mid- 1980s. It had to close in 2002 due to reduced prices and environmental problems but is planning to produce REEs again in 2012 (USGS, 2002).
In the late 1970s the Chinese production of REE increased due to developed mining techniques and governmental support also due to research and development of rare earth supplies. From 1978 to 1989 the production increased by 40 % (see figure 21). Many mining companies during this period were not making a profit, but could still continue their production due to financial support from banks that were controlled by the Chinese government and non-performing loans. Because of this it was possible to produce the REEs at low prices and increase the export. The increased export made prices drop considerably in the beginning of the 1990s and producers situated outside of China were not profitable anymore and had to close down and the Chinese production increased (see figure 21) (Levkowitz, et al, 2010). Production from ion adsorption clay in southern China began in the 1990s mainly due to an increased yttrium demand (Castor and Hedrick, 2006).

Australia produced REEs from monazite sands until 1995. Russia has been an important REE producer from hard rock’s until the Chinese production decreased the prices (Castor and Hedrick, 2006).
Processing of monazite containing beach sands have been banned in Europe, Australia and China due to radioactivity (BGS, 2010). The production has increased steadily with some dips. In 2008 the production decreased due to the financial crisis.

Since the REEs cannot be mined separately, increasing production because of shortage of a certain metal creates overproduction if other metals. Overproduction leads to decrease in price. China experienced problems regarding this in 2001 and therefore decreased production which resulted in supply shortage for some metals (BGS, 2010).

5.3.2 Current production of REE

China is the dominating producing country with over 95% of the market of REE. The Chinese production in 2010 was 130,000 tons. Apart from China India, Brazil and Malaysia also produced REEs. India produced 2700 tons, Brazil 550 tons and Malaysia 350 tons of REO (USGS, 2011b). Elsner (2011) has other numbers of the production of REO in 2010, stating that China produced 118,900 tons, USA 1,483 tons, Russia 1,495 tons and India about 35 tons. All together that is a production of 121,913 tons of REO. Bayan Obo, the largest mine, produced 55 million tons of REO as a by-product to iron. The ion adsorption clay produced 25,000 tons REO as a main product. About 90% of the REO production is a by-or co product. Regarding to BGS (2011) the only significant REO source outside of China was Russia with a production of 2,500 tons REO.

5.3.3 China export quotas

In 1990 rare earths were declared to be a strategic mineral, which restricted other foreign companies to participate in rare earth mining projects without approval from the State development and planning commission and ministry of commerce, unless they cooperated with a Chinese company. Since the beginning of the 1990’s China Ministry of land and resources has been in charge of strategic commodities production plans which include export quotas, production quotas for the country and different provinces. The export quotas can be seen in table 5. The production has been much higher than anticipated and most of the overproduction was done by miners without proper licenses and with outdated techniques. These techniques caused environmental damage. Since the consumption of rare earth products in China increased by 380% in less than 10 years, quotas where needed to maintain the
metals for their own use. In 2005 trade of rare earth concentrate was banned and rebates on REEs were no longer allowed. Export of products containing REEs were encouraged, since until 2010 there were no quotas on products containing rare earths but only on the oxides, salts and metals (Tse, 2011). The foreign joint companies have lower export quotas than the domestic ones (DOE, 2010).

<table>
<thead>
<tr>
<th>Year</th>
<th>Export quotas [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>65 609</td>
</tr>
<tr>
<td>2006</td>
<td>61 821</td>
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<tr>
<td>2007</td>
<td>59 643</td>
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<tr>
<td>2008</td>
<td>56 939</td>
</tr>
<tr>
<td>2009</td>
<td>50 145</td>
</tr>
<tr>
<td>2010</td>
<td>30 258</td>
</tr>
</tbody>
</table>

Table 5, Chinas export quotas (DOE, 2010)

5.4 Recycling and substitution

It is a common opinion that since metals are recyclable there will be no shortage on the market for them. Even though it is potentially possible to recycle metals it is not possible to have a market that is infinitely large since if everything is used in applications, something has to be torn down to actually reuse the metals. Recycling rate of critical metals usually less than 1 % and they can be difficult to substitute. (BGS, 2011) If the products contain small amount of the metal it is not economic to recycle them unless the price of the metal increases. Both lithium and neodymium can be substituted onto other metals however the performance will not be as good and efficient.

5.4.1 Recycling and substitution of lithium

There are many companies in Germany, Japan and the U.S which are awarded money to set up a lithium ion battery recycling facilities (Jaskula, 2009). There are different methods for recycling, and it is not very common to actually recycle lithium. About 590 tons of lithium was available in cell phone batteries from 1996 to 2005, and only about 10 tons were recycled (Wilburn, 2008). When recycled the recovery rate was estimated to be over 90 % (Gruber et al, 2010). EU has set a goal that 45 % of all the portable electronics batteries should be recycled by 2016 (Schuler et al, 2011). Even though the metals can be recycled it does not increase the total amount of the metals merely keeping them in the system to reuse them.

There is an American company, Toxco, who specializes in recycling batteries of all types, for example lithium batteries. The battery waste is stored in bunkers and if reactive it is cooled down to prevent chemical reactions, then the batteries are shredded and the metals are separated. The lithium is converted into lithium carbonate (Toxco, 2003).

Li-ion batteries could be substituted to NiMH batteries, but neodymium could become a limiting factor in these batteries and thereby other batteries have to be taken into consideration.

5.4.2 Recycling and substitution of neodymium

Recovery and recycling of REEs are difficult due to their similar properties and since they are often used together in compounds. The cost for separating the REEs often makes it uneconomic.
There are different techniques for separating REEs from different products. REEs used in NiMH batteries anode and cathode part can be separated using both chemical and physical methods (Ito et al, 2009). The method involves crushing after that the REE containing components are chemically treated with dissolution and melting to separate the metals. It is then possible to recover the REEs, the purity was high, but has to be treated further to increase it to an acceptable level. Both shape and assembly of the battery can affect the efficiency of the process (Ito et al, 2009).

While making the neodymium magnets about 50 % of the material used is discarded as scrap or waste, due to impurities and sludge products. Neodymium forms very stable compounds with for example oxygen which makes is it impure and therefore unusable. If an efficient recovery process were available neodymium would last longer. There is a process where neodymium could be extracted by adding magnesium and using it as extraction medium. Then the REE containing liquid could be treated with hydrometallurgical methods to extract the REEs (Takeda et al, 2006). Similar methods could be used to recover REEs from computer monitors (Eriksson et al, 2011).

The expansion of wind power is not dependent on neodymium but since it is more efficient it would be advantageous to use it. To be able to create small laptops and iPhones neodymium magnets are needed since other magnets have lower magnetic strength and therefore have to be larger. Praseodymium (Pr) (another REE) is interchanged with neodymium in permanent magnets. The demand for Pr is not very high in other applications (Schuler et al, 2011).
6. Time series

6.1 Introduction

Time series are a method of investigation of the future production based on the historic production. The historic production of neodymium and lithium is fitted to different curve models described in this chapter. For future energy prognosis mainly bell-shaped curves have been used (Bardi et al, 2005). They are generally easier to fit to the market and technology than exponential curves because they have a limited growth. The cumulative production will be a sigmoid curve (s-shaped curve), which have a slow growth in the beginning and end. Some of the most known functions are; Logistic, Gompertz, Bertalanaffy, Brody and Richards. Richards were developed later and is more general since it has an extra parameter. The curves have been used to model oil production, with limited reserves and the knowledge that oil and fossil fuels follows sigmoid behavior (Höök et al, 2011).

In 1949, Hubbert, pointed out that production of oil will eventually reach a peak since it is a non-renewable reserve. By using a logistic curve model the peak in the American oil production was predicted based on historic production with a restriction of limited reserves. The peak occurred the predicted year. Minerals show a similar behavior as oil when it comes to using curve models to estimate the peaks. Bardi (2005) showed that mineral production almost always results in bell-shaped curves, however the shape does not have to be symmetric. Bardi and Pagini (2008) concluded that bell-shaped curves can be used globally and for most minerals when examining 57 minerals from the USGS database. The results obtained by using a logistic curve were that 11 of those minerals already had peaked in production. It is reasonable to assume that the other minerals will behave similarly. Logistic curves are always symmetric and therefore other curves which are not necessarily symmetric could be needed when making time series based on minerals. The curves has been used to visualize that in the future supply might not meet demand (May et al, 2011). Mineral resources will not be completely depleted, but the cost of extracting the minerals will eventually be too high, due to lower concentration and quality. Improved technology could increase the amount of reserves however if the reserves are overestimated there will be a more rapid production decrease. A rapid decrease could become a problem for the economy and society (Bardi, 2005).

Differences between peak oil and peak minerals are that minerals can be recycled. Due to that the estimates of the amount of available minerals are less reliable than those of oil. (Höök et al, 2011) There are large difficulties with the availability of data for minerals often due to different estimations of reserves and resources with different standards as shown before. It is difficult to make an exact prediction about the peak year due to social and economic factors that are not clearly stated, however, the peak can be predicted within a range of time (Bardi et al, 2005).

The main restraint to production is availability. Finite resources have an upper limit in cumulative production due to geological abundance, the ultimately recoverable resources (URR) is the limiting factor. These models cannot account for political, economic and other dynamic processes which occur in reality and makes fluctuations to the production. Therefore these curves should be used for long term growth and trends. The only limiting factor is the geology, thereby the models is an assumption of a free market (Höök et al, 2011). That is a scenario where it is possible to extract all recoverable reserves which is probably unrealistic in reality but it shows the absolute limit to what is possible to recover and the limit to what could be possible in the future.

Time series is based on a uniformly spaced number of data points, for example annual mine production. It is a good model for forecasting, which is composed of other methods to be able to extract
statistics and characteristics typical for the studied data (Höök et al, 2011). Curve models can help the understanding of the underlying physical properties of a system (Bardi et al, 2005).

It is not enough just to have a curve model but the data can be fitted to the data already given. To make the data fit to the historic production different techniques can be used, such as the least square method or other regression techniques. The deviation from the data points is the sum of squares of difference between curve and actual data points, which should be minimized. Polynomials with \((n-1)\) terms are the best fit for \(n\) data points. The terms have no real physical meaning and do not naturally have a reliable behavior for extrapolating. Physical models does not have that many parameters, however the curves is only a mathematical tool. There are other problems, if too many parameters are used then the curves describe the noise instead of the data (Höök et al, 2011). The data used limits how good the curve will be. If the data set is unreliable then the curve fitted for the data set will not tell much about the future.

6.1.1 Microsoft Excel Solver

The generalized reduced gradient method (GRG2) is used by Excel for non-linear problems. The URR is not used as a fitting parameter, but is initially given based on different studies for these elements. The GRG2 method is an iterative method which is good for large amounts of data. In these models the solver minimized one cell by changing other cells which could have restraints put to them. The convergence is better if more restraints are added. (More detailed in Billo, 2007 and de Levie, 2001.)

The constraints and the optimal cells are functions of adjustable cells, if the functions are derived the first derivative measures the rate of change when the input varies. Since there are several values entered the function have many partial derivatives which then measure the rate of change with respect to each other, which then becomes a gradient. The gradient decides how the adjustable cells should be changed depending on sign of the derivative. (Microsoft, 2003)

The values of the derivatives are varied and the changing rate is observed, finite differences. Forward differencing uses a value close to the current point and calculates the derivative. Central differencing is another method with two points in different directions from the current point, which requires more calculations but it is more accurate. (Microsoft, 2003)

If the gradient is zero, the minimum has been found, but if not zero the approximation is made by exchanging the function to its Taylor expansion around \(x_k\), and thereafter the function is solved for \(x_k\) instead.

The convergence slows down after some iteration. It is a good method for an approximate solution, and for a more reliable solution other methods should be used. The prognosis that are made are a scenario, but the future cannot be predicted exactly. These models are a good prognosis with the limited data that is available.

6.2 Curve models

There are different functions that will be used when fitting the historic production to a model, the Logistic, Gompertz and Richards’s model will be used. Both the Gompertz and Logistic curve are special cases of the more complex Richards curve. It is good to have a range of different models because the reserves are dynamic and there are variations in the data as well. The only restraint in the models will be the geological availability and a depletion rate of maximum 5 \%. 
It is shown that the peak of oil fields usually occurs when about 40% has been extracted, which can only happen if the curve model is asymmetric, such as Gompertz and Richards’s models. The peak of the logistic curve always occurs when 50% of the reserves have been extracted (Höök et al, 2011). The logistic curve is chosen because it is very well known, but it is also critiqued because it peaks when 50% of the URR is extracted. Therefore it is good to include asymmetric curves such as Richards and Gompertz. Both the logistic and the Gompertz are extreme cases of the Richards’s function. The logistic curve will have the highest peak production and Gompertz the lowest, the Richards curve is in between. It would be possible to use more models but some restrictions has to be made and therefore the extreme cases and the general case are used.

The logistic function will firstly increase exponentially, when the extraction is a small fraction of the URR. k dominate the behavior of the curve in the beginning, later on however when the cumulative production grows and becomes an large part of the URR, the extraction becomes more difficult and the extraction rate decreases. Finally production will be zero due to the finite limit of resources (Höök et al, 2011). Since reserves are dynamic, the curve can only represent an approximation of the future production.

When fitting the curve to the historic production the least squares of annual reported production and annual assumed production is minimized by changing peak year and growth rate. One restraint that is added is that the depletion rate cannot be higher than 5%.

The parameters used are:

URR: Ultimately recoverable resources
k: growth rate parameter
t₀: peak year
M: Exponent

6.2.1 Richards function

\[ y(t) = URR \times (1 \pm e^{(\frac{t-t_0}{M})})^M \]  

[Eq 4]

If M > 0 then the first sign is negative, and if M < 0 then the first sign is positive.

The Richards function is a generalized logistic function. Both the Gompertz and the Logistic functions are a special case of the Richards function which is more general. Richards has one more parameter, M, than the other two curves which makes in more complex, but also more accurate. The extra parameter makes it more difficult to work with. It is very sensitive with respect to the initial values. The Logistic function is a special case with M = -1, and the Gompertz function is another special case with M -> infinity. Historically it has been used for growth modeling of biological systems and then later used for modeling energy systems (Höök et al, 2011).
6.2.2 Logistic function

\[ y(t) = \frac{URR}{1 + e^{-k(t-t_0)}} \]  \[\text{Eq 5}\]

The logistic curve was discovered in 1800’s and then used in relation to population growth, later also as tumor growth. The logistic curve is a symmetric curve which is used in a range of applications such as chemistry, statistics, economics and political science and it has been used to model peak oil by several researchers (Prior et al, 2011, Höök et al, 2011).

6.2.3 Gompertz function

\[ y(t) = URR \times e^{(-e^{(-t^k(t-t_0)))}} \]  \[\text{Eq 6}\]

The Gompertz curve is an asymmetric curve. The left of the curve is steeper, and the asymptote is approached more directly whereas the right part is approached more gradually. It is one of the S-shaped curves. These curves have a slow growth in the beginning and end stages. It was used for modeling tumor growth in the 1960’s and has been a good model for energy systems since there is an upper limit of production which energy systems have. Unbounded growth would result in unrealistic predictions (Höök et al, 2011). The function has also been used to prognosticate the peak oil and peak coal. It has a soft decline rate and models a more sustainable production than the logistic function.

6.3 Depletion rate

The depletion rate is the percentage of the annual production to the reserves left in the ground.

The depletion rate is:

\[ d_{dt} = \text{Annual production} / (\text{Ultimately Recoverable Reserves} – \text{Cumulative production}) \]  \[\text{eq 7}\]

The depletion rates for minerals are not commonly known. The depletion rate for the U.S.’ copper production was 4.27 % (USGS, 2011c) and the depletion rate for South Africa’s gold production was 4.08 % (Bardi, 2011, personal correspondence). Therefore putting a limit to the depletion rate of 5 % appears to be a reasonable restraint. The depletion rate of coal reaches a maximum of 3 % which is showed in extensive studies by Höök et al (2009). Investigating different scenarios with different URR and depletion rates could give interesting outcomes. If there is no depletion rate the curves can be very steep and then abruptly decrease to no production, which is not a very realistic scenario, especially the logistic curve can behave unrealistically if not restraint.
7. Results

The production data are from 1900 until 2009, while the prognoses are until 2100. These prognoses give a spread in the estimations, with some variations. It cannot be said today how the production will develop over the century, due to that it is relevant to have different estimations. The URR (Ultimately recoverable resources) are varied to see how much difference it makes. The logistic Hubbert curve was a very good estimate for the oil production in the U.S. Not all production follows a symmetric curve which has given rise to some problems when assuming so. Even though the URR differs quite considerably, the peak does not move that much which is due to an exponential behavior which the bell-shaped curves have (Höök et al, 2011).

7.1 Lithium prognosis

The URR used are 15, 30 and 60 million tons. The average current estimation is 15 million tons, but varies up to 30 million tons, and prognosis when the URR is 60 million tons is therefore quite unrealistic but included anyway to compare the different prognosis.

USGS’s historic lithium production is reported in gross product of lithium, and not in lithium metal production. From 1974 BGS has reported production on lithium metal. The lithium concentration in the gross product is calculated from BGS data, and is on average 6 %, the concentration is decreasing though as seen in figure 23. An exponential trend line is added, it is exponential since the concentration goes to zero with time which the exponential curve also does. When doing the least square method to determine the equation the result is the same.

The depletion rate is constantly below 3% in these prognoses.

![Lithium concentration, BGS](image)

**Figure 23, Lithium concentration from 1974 to 2009, (BGS)**
Figure 24, Gross production of lithium, with URR: 250 Mtons, and lithium concentration estimated to be constant 6% also in the future.

Figure 25, Lithium metal production, URR: 15 Mtons, 3% depletion rate
**Figure 26**, Cumulative lithium metal production, URR: 15 Mtons, 3% depletion rate

**Figure 27**, Lithium metal production, URR: 30 Mtons, 3% depletion rate
Figure 28, Cumulative lithium production, URR: 30 Mtons, 3% depletion rate

Figure 29, Lithium metal production, URR: 60 Mtons, 3% depletion rate
Table 6, Peak year of production of lithium metal dependent on estimated ultimately recoverable resources

<table>
<thead>
<tr>
<th>URR [Mtons]</th>
<th>Logistic</th>
<th>Gompertz</th>
<th>Richards</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2082</td>
<td>2127</td>
<td>2106</td>
</tr>
<tr>
<td>30</td>
<td>2095</td>
<td>2164</td>
<td>2113</td>
</tr>
<tr>
<td>60</td>
<td>2110</td>
<td>2203</td>
<td>2133</td>
</tr>
</tbody>
</table>

7.2 REO prognosis

The available data for REEs are limited, and data for neodymium is even scarcer. More data is needed to make better and reliable prognoses. Currently the average estimations of the reserves are 110 million tons and therefore a prognosis is made with 110 million tons and another optimistic scenario with an URR of 200 million tons. A maximum of 5% depletion rate is applied.

![REO production 1900-2100](image)

Figure 30, REO production, URR: 110 Mtons, 5 % depletion rate
**Figure 31**, Cumulative REO production, URR: 110 Mtons, 5% depletion rate

**Figure 32**, REO production, URR: 200 Mtons, 5% depletion rate
<table>
<thead>
<tr>
<th>URR [Mtons]</th>
<th>Logistic</th>
<th>Gompertz</th>
<th>Richards</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>2073</td>
<td>2114</td>
<td>2082</td>
</tr>
<tr>
<td>200</td>
<td>2082</td>
<td>2140</td>
<td>2101</td>
</tr>
</tbody>
</table>

*Table 7*, Peak year of REO production based on different ultimately recoverable reserves

### 7.3 Neodymium prognosis

The concentration of neodymium oxide in REO is usually around 18.5 % as discussed earlier. By using that number the reserves of neodymium oxide are estimated to around 20 million tons and the reserves of neodymium are about 17.1 million tons. One prognosis has URR of 17 million tons and another more optimistic prognosis has a URR of 30 million tons. The depletion rate is varied between 3% and 5% to see whether that makes a difference.

![Nd production 1900-2100](image)

*Figure 33*, Neodymium production, URR: 17 Mtons, 3% depletion rate
Figure 34, Cumulative neodymium production, URR: 17 Mtons, 3% depletion rate

Figure 35, Neodymium production, URR: 17 Mtons, 5% depletion rate
**Figure 36**, Cumulative neodymium production, URR: 17 Mtons, 5% depletion rate

**Figure 37**, Neodymium production, URR: 30 Mtons, 5% depletion rate
**Figure 38**, Cumulative neodymium production, URR: 30 Mtons, 5 % depletion rate

**Figure 39**, Neodymium production, URR: 30 Mtons, 3 % depletion rate

<table>
<thead>
<tr>
<th>URR [Mtons]</th>
<th>Logistic</th>
<th>Gompertz</th>
<th>Richards</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>2068</td>
<td>2108</td>
<td>2085</td>
</tr>
<tr>
<td>30</td>
<td>2078</td>
<td>2133</td>
<td>2094</td>
</tr>
</tbody>
</table>

**Table 8**, Peak year of neodymium production
7.4 Future production

7.4.1 Lithium

The lithium carbonate production is estimated to 134,000 tons in 2010 and to 250,000 tons in 2015, converted to lithium metal that is 25,283 tons in 2010 and 47,170 tons in 2015 (DOE, 2010).

If the lithium reserves are 15 million tons, the production in 2015 according to the prognoses are 27,475 tons, 23,132 tons and 28,110 tons respectively. These numbers are quite small and for a larger increase the URR needs to be higher, or otherwise the prognoses do not match the future production very well. It does not seem like DOE’s estimated production in 2015 can be reached if the reserves are 15 million tons. If the reserves are 30 million tons according to the prognoses the production will range from about 23,000 - 30,000 tons. This is almost the same result as with 15 million reserves.

7.4.2 Neodymium

According to BGS the REO production forecast outside of China for 2011 is 5,750 tons. For 2012 it is 56,800 tons and 2013 it is projected to be 129,000 tons of REO, mainly produced from Mountain Pass, Mount Weld and Nolans Bore (BGS, 2011). The current production is 133,000 tons, and over 95 % comes from China. Chen (2011) estimates the REO production outside of China to be more than 170,000 tons 2015. In 2013 if the projects are running without complications China’s production could be reduced to be 64 % of the total production according to Chen (2011). This seems very unlikely given the current status of projects and the world market. Currently the demand of REO outside of China is 50,000 tons. Chen (2011) estimates a 15 % increase of demand outside of China at least until 2015, which would be a demand of 115,600 tons in 2015 which is a large gap to fill. DOE (2010) also estimates the production of future REE projects, the estimated REO production for 2010 is 127,315 tons and the estimated production for 2015 is 187,962 tons. The neodymium production is estimated to 21,304 tons in 2010 and to 30,657 tons in 2015. DOE’s estimation is more realistic, but much depend on the economy of the world which is now unstable.

When looking at the curve fittings it is possible to see that for the production to double from today to 266,000 tons it takes until 2022 for the logistic curve, which is the curve that is increasing the most. In 2013 the production will be 167,300 tons. However that is based on the already existing data and a new mine which could begin producing large quantities immediately could make the predictions unreliable. There were 393 REO development projects at different stages (BGS, 2011). It takes about 10 years to make an REE mine operate and be profitable according to Nickels (2010). Many companies who are looking into investing in REE mines are too small to actually be able to start mining due to the large initial investments required in advance.

For a deposit to be economic it is necessary that the concentration of HREE is substantial. HREE are expensive to mine also in China whereas LREE are relatively cheap. However, the price is still comparably low and therefore the mined amount is not as high as it could be. China could be mining more LREE than they are currently doing but not mining more of them increase the price. About 90 % of the market for REO’s is in South East Asia, mainly in China and Japan. Stockpiling could become important for countries to secure their supply (Lifton, 2011).
8. Future scenarios

To see what the results mean for the future production of wind turbines, batteries and permanent magnets some scenarios will be presented. It is an important to know whether the lithium and neodymium production is sufficient to meet the demand for these metals. Some scenarios based on the production will be investigated in this chapter.

### 8.1 Vehicles

There are different ways of electrifying the transport sector. It is done by using different techniques for motors and batteries. Batteries in vehicles have mainly been NiMH batteries. Wilburn, (2008), estimates the percentage to be about 95 % NiMH batteries in hybrid vehicles. It is believed that Li-ion batteries will be the dominating battery for electric cars in the future, since they are more advantageous, as discussed in chapter 1. In the future, fuel cells and ultra-capacitor batteries could perhaps replace lithium ion batteries (Gruber et al, 2010). Some vehicles use motors with permanent magnets, (Nd – magnets), to improve the efficiency, which increases the demand of neodymium in vehicles (Scuhler et al, 2011).

The current car fleet consists of about 600 million passenger cars and about 1.1 billion vehicles are in use. The production of passenger cars in 2010 was 58,478,810 and the production of both cars and commercial vehicles were 77,857,705 (OICA, 2010). In 2009 the number of hybrid car sale in the USA was almost 300 000, and the sale of passenger cars were 5,456,246, the hybrids accounted for 5.5 % (Hybrid Car, 2011).

The amount of EVs (electric vehicles), HEV (hybrid vehicles) and PHEV’s (plug in hybrid vehicles) are uncertain in the future. The estimations differ considerably, due to many different factors such as price and availability of diesel and gas, infrastructure and social factors, which are impossible to know today. The estimations range from 2.1 million vehicles sold in 2014 to a cumulative sale of 9-14 million sold by 2015 (Schuler et al, 2011). IEA (2009) concluded that a total of 1.5 million hybrid and electric vehicles had been sold worldwide during 2000 – 2010.

The future for alternative vehicles is difficult to predict, there are many estimates about it. About 3-10 % of the new cars sale will be electric or hybrids by 2020 – 2025. (ACEA, 2011) If the number of new sales remain constant at about 60 million cars per year then that would mean that the sale of electric and hybrid cars would be 1.8 – 6 million in 2020 - 2025. IEA (2009) estimates the annual sale to be 0.7 million PHEV’s and 0.5 million EV’s by 2015 and 5 respectively 2.5 million by 2020. By 2050, 50 million vehicles are estimated to be sold each year.

### 8.2 Lithium

#### 8.2.1 Portable electronics

Portable electronics is a large market for lithium batteries. Gruber et al, 2010, estimates the average mass of 1.07 tons of lithium per million batteries for primary and secondary portable batteries in 2008. The total amount of lithium used for batteries were 4 700 tons.

The amount of lithium required in a mobile phone is 0.3 g. About 1 470 tons of lithium would be required if 70% of the earth’s 7 billion people would have a mobile phone with a li-ion battery.

Regarding to UN data about mobile subscriptions, over 70 % (87%) of the population has a subscription (UN, 2010a). Furthermore if around 30 % (UN, 2010b) of the people on the earth would
have a laptop with a lithium ion battery, with about 5 g lithium, (Wilburn, 2008, JGMEC, 2009), it would require 11 550 tons of lithium. In the future the portable electronics market is not decreasing so an increase of lithium ion batteries is likely. From 1996 to 2005 the lithium ion batteries in laptops increased from 3.3 tons to 99 tons. Li-ion batteries accounted for 92 % of the market for laptops in 2005 (Wilburn, 2008). Regarding to Pillot (2009), 160 million portable computers were sold in 2009, 100% of them had Li – ion batteries, assuming that each battery contain 5g lithium that is 800 tons of lithium. The demand for lithium in portable electronics continues to grow.

8.2.2 Fusion
The annual consumption of lithium for a 1.5 GW fusion is according to Smith et al (2010) 3.65 – 7.3 tons of lithium. Fasel and Tran (2006) estimates the amount of lithium in a 1.5 GW reactor to be from 174 – 787 tons, the lower number as a blanket and the higher number is if used as both breeder and as a coolant. Regarding to Table 9, the annual lithium consumption is quite low, depending on the installed effect.

<table>
<thead>
<tr>
<th>Installed effect [GW]</th>
<th>Annual lithium consumption [tons]</th>
<th>Lithium consumption for 40 years [tons]</th>
<th>Lithium in the reactor [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>23-46</td>
<td>920-1 840</td>
<td>1 100 - 4 980</td>
</tr>
<tr>
<td>370</td>
<td>1 147 - 2 047</td>
<td>42 920 - 81 800</td>
<td>42 920 - 194 800</td>
</tr>
<tr>
<td>1000</td>
<td>2 433 - 4 866</td>
<td>97 300 - 194 600</td>
<td>116 700 - 525 300</td>
</tr>
</tbody>
</table>

Table 9, The amount of lithium required for fusion, daily consumption is 10 – 20 kg, and the amount required to build a reactor is between 174 – 787 tons.

The electricity generation in the world in 2010 was 21 000 TWh. If fusion had an efficiency of 80 %, and the installed effect was 1000 GW, that would generate about 7 000 TWh in one year which would be a third of the world’s electricity generation.

If 1000 GW of fusion was installed it would require more than 100 000 tons of lithium just to build the reactors, which is five times the current annual lithium production. This is under the assumption that lithium was only used as a blanket, which would require 174 tons per 1.5 GW.

A problem with fusion is that it is preferable to use $^6$Li instead of $^7$Li which is much more abundant in the earth’s crust. $^6$Li only constitute about 7.4 % of the total lithium content. To enrich the mix with $^6$Li could become a problem which makes it more expensive.

8.2.3 Vehicles with li – ion batteries
The amount of lithium needed for the types of cars differs depending on the source and the effect needed. The battery capacity today for an EV is around 25 kWh, a PHEV need around 12 kWh and a HEV need 2 kWh. Falâs et al (2010) uses other numbers; the battery capacity of EV’s are in the range of 15 – 30 kWh, the capacity for the PHEV is around 10 kWh. The energy density also varies, 0.11 kg Li/kWh according to Chemetall and 0.1-0.17 kg Li / kWh according to Falâs (2010).
If a tenth of the passenger cars would be exchanged to hybrid or electric cars, and the amount of lithium per car would be 1.0 kg in average, it would require 65 950 tons of lithium. As shown in table 10, there are large variations of the amount of lithium needed. To make a scenario, (see table 11), a value of 1.5 kg lithium/car is used. That is in the lower limit of what seems to be needed in a PHEV. It is a rather low value but it is used not to overestimate the lithium metal needed.

<table>
<thead>
<tr>
<th>Nr of vehicles [million]</th>
<th>Lithium battery [%]</th>
<th>Amount of lithium in battery [kg]</th>
<th>Lithium metal needed [tons]</th>
<th>Lithium battery [%]</th>
<th>Amount of lithium in battery [kg]</th>
<th>Lithium metal needed [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>1.5</td>
<td>750</td>
<td>70</td>
<td>1.5</td>
<td>1 050</td>
</tr>
<tr>
<td>21</td>
<td>50</td>
<td>1.5</td>
<td>1 575</td>
<td>70</td>
<td>1.5</td>
<td>2 205</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>1.5</td>
<td>3 750</td>
<td>70</td>
<td>1.5</td>
<td>5 250</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>1.5</td>
<td>6 750</td>
<td>70</td>
<td>1.5</td>
<td>9 450</td>
</tr>
<tr>
<td>14</td>
<td>50</td>
<td>1.5</td>
<td>10 500</td>
<td>70</td>
<td>1.5</td>
<td>14 700</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
<td>1.5</td>
<td>15 000</td>
<td>70</td>
<td>1.5</td>
<td>21 000</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>1.5</td>
<td>37 500</td>
<td>70</td>
<td>1.5</td>
<td>52 500</td>
</tr>
</tbody>
</table>

**Table 11**, Estimate of lithium metal needed based on the number of vehicles produced

### 8.2.4 Lithium demand

If a total amount of 5 million vehicles are built by 2015, and 70 % of them uses a li-ion which in average requires 1.5 kg lithium the total demand of lithium is 5 250 tons. That will not be a problem until 2015 as can be seen in table 12, if the increased production is for these batteries and other application use the same amount as earlier.

<table>
<thead>
<tr>
<th>URR [Mtons]</th>
<th>Logistic</th>
<th>Gompertz</th>
<th>Richards</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>28 307</td>
<td>19 689</td>
<td>23 118</td>
</tr>
<tr>
<td>30</td>
<td>28 818</td>
<td>20 777</td>
<td>25 874</td>
</tr>
<tr>
<td>60</td>
<td>29 119</td>
<td>21 692</td>
<td>27 235</td>
</tr>
</tbody>
</table>

**Table 12**, Production of lithium metal in 2015
If 50 million EV-, HEV- and PHEV’s should be sold annually in 2050, as IEA’s (2009) scenario estimates. The lithium demand would be 37 500 – 52 500 tons if powered to 50%/70% with lithium ion batteries based on an average of 1.5 kg lithium per car.

<table>
<thead>
<tr>
<th>URR</th>
<th>Logistic</th>
<th>Gompertz</th>
<th>Richards</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>109 918</td>
<td>38 822</td>
<td>69 786</td>
</tr>
<tr>
<td>30</td>
<td>128 875</td>
<td>46 000</td>
<td>89 220</td>
</tr>
<tr>
<td>60</td>
<td>140 312</td>
<td>52 485</td>
<td>82 446</td>
</tr>
</tbody>
</table>

**Table 13**, Annual production of lithium metal in 2050

If the lithium production follows Gompertz or the Richards prognoses and has an URR of 15 million tons, it is not possible to meet the demand for lithium ion batteries for vehicles by 2050. If the URR is higher, 30 million tons, and follows the logistic prognosis it is possible if the production only is used li-ion batteries to vehicles.

<table>
<thead>
<tr>
<th>Lithium metal for 50 million vehicles [tons]</th>
<th>Lithium metal for 150 GW fusion [tons]</th>
<th>Total demand [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>37 500 – 52 500</td>
<td>17 400 – 78 700</td>
<td>54 900-131 200</td>
</tr>
</tbody>
</table>

**Table 14**, Total demand of lithium

<table>
<thead>
<tr>
<th>URR</th>
<th>Logistic</th>
<th>Gompertz</th>
<th>Richards</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>185 157</td>
<td>61 149</td>
<td>110 575</td>
</tr>
<tr>
<td>30</td>
<td>362 280</td>
<td>104 300</td>
<td>241 860</td>
</tr>
<tr>
<td>60</td>
<td>716 530</td>
<td>182 175</td>
<td>382 200</td>
</tr>
</tbody>
</table>

**Table 15**, Production peak year

### 8.3 Neodymium

#### 8.3.1 NiMH batteries and permanent magnets

There are a range of estimations regarding the amount of neodymium or neodymium oxide content in cars. Some numbers include both permanent magnet in motors and a NiMH battery, while others might just include one of them. Olsson, (2011), have estimates of a Toyota Prius, where the neodymium content is, 300 – 600 g for the permanent magnet, and about 900 g for the battery. According to DOE (2010) the amount of Nd needed in a NiMH battery for hybrid vehicles is 0.2 – 0.31 kg. The neodymium content in a NiMH battery is 10 % (Wilburn, 2008).

Some electric and hybrid cars also have neodymium permanent magnets in the motor, and sometimes that is included in the number other times it is not depending on the motor in the car. DOE (2011) and Olsson (2011) estimates the average weight of magnets per vehicle to be 1 – 2 kg, and the neodymium oxide content to be 31 %. This is based on an assumption that the motor uses permanent
magnets, which do not have to be the case in the future. It is not specified whether the content is given in neodymium or neodymium oxide which also creates a problem.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Car</th>
<th>Nd content [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schuler et al, 2011</td>
<td>Toyota Prius</td>
<td>0.19 -1.8</td>
</tr>
<tr>
<td>Jacobson et al, 2011</td>
<td>Toyota Prius</td>
<td>0.2 - 1.0</td>
</tr>
<tr>
<td>Hirai, 2011</td>
<td>Toyota Prius</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>DOE, 2011</td>
<td></td>
<td>0.31 - 0.62</td>
</tr>
<tr>
<td>Olsson, 2011</td>
<td>Toyota Prius</td>
<td>1.2 - 1.5</td>
</tr>
</tbody>
</table>

**Table 16**, Estimate of kg neodymium required in cars

Schuler et al's (2011) estimate of neodymium in a Toyota Prius range from 0.19 – 1.8 kg. The higher number is could include both the magnet and the battery, but the lower number could perhaps include only one of them. The other low estimates are probably only including either the permanent magnet or the battery. Due to limited information it is very difficult to know what is actually included in the numbers. Currently the NiMH battery is most common in HEV and EV's, however that is changing to li–ion batteries. There are different kinds of motors in these cars and which will be used in the future depends on economy and availability of materials.

Below are some different scenarios. It is difficult to know the amount of neodymium used depending on if it is used in both battery and motor, therefore an estimation of 1 kg per vehicle is quite low.

<table>
<thead>
<tr>
<th>Nr of vehicles [million]</th>
<th>NiMH battery [%]</th>
<th>Amount of Nd in battery [kg]</th>
<th>Nd metal needed [tons]</th>
<th>NiMH battery [%]</th>
<th>Amount of Nd in battery [kg]</th>
<th>Nd metal needed [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>1</td>
<td>500</td>
<td>70</td>
<td>1</td>
<td>700</td>
</tr>
<tr>
<td>2.1</td>
<td>50</td>
<td>1</td>
<td>1 050</td>
<td>70</td>
<td>1</td>
<td>1 470</td>
</tr>
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<td>50</td>
<td>1</td>
<td>2 500</td>
<td>70</td>
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</tr>
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<td>1</td>
<td>25 000</td>
<td>70</td>
<td>1</td>
<td>35 000</td>
</tr>
</tbody>
</table>

**Table 17**, Estimate of the neodymium content in vehicles by 2015

**8.3.2 Wind power**

DOE (2010) has estimated different scenarios for direct driven turbines, a low intensity and a high intensity scenario. Their assumption is that 31 % of the magnet is neodymium oxide, and the average weight of a magnet per MW is then from 0.4 tons for the low intensity scenario and 0.6 tons for high intensity scenario. The neodymium oxide content would then be ranging from 0.124 – 0.186 tons/MW, (0.105 – 0.159 tons Nd/MW) for a direct driven turbine (DOE, 2010). There are many other numbers regarding how much neodymium is needed in a turbine, for example Jacobson et al (2011) estimated it to 0.2 – 0.6 tons/MW. That number is almost consistent with DOE’s estimate of the total magnet weight.
The estimated numbers of gearless wind turbines differ from 10 – 20 % of the newly installed wind power. Currently 14 % of the newly installed wind turbines have a gear-less design and uses permanent neodymium magnets, (Schuler et al, 2011), therefore an assumption of 14 % of the newly installed wind turbines will be gearless is a reasonable approximation.

<table>
<thead>
<tr>
<th>Installed wind power [GW]</th>
<th>Nr of direct driven turbines [%]</th>
<th>Nd content [kg/MW]</th>
<th>Total Amount of Nd [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>14</td>
<td>105</td>
<td>2 940</td>
</tr>
<tr>
<td>300</td>
<td>14</td>
<td>105</td>
<td>4 410</td>
</tr>
<tr>
<td>600</td>
<td>14</td>
<td>105</td>
<td>8 820</td>
</tr>
</tbody>
</table>

**Table 18**, Estimate of the amount of neodymium needed depending on the installed effect.

If assuming one of IPCC’s (2011) scenario with a growth of between 200 – 300 GW installed effect, until 2015. Also assuming that the direct driven turbines will constantly be 14 %, and the Nd2O3 content is between 0.12 – 0.19 tons /MW (0.1 – 0.11 tons of Nd/MW) the amount of Nd2O3 needed ranges from 3 360 – 7 980 tons until 2015, which is 2 880 – 6 840 tons Nd. If 100 % of the wind turbines are direct driven it would require 31 500 tons of Nd to install 300 GW.

### 8.3.3 Nd/REE used for other applications

If REE magnets are used in more applications such as in air conditioners and for magnetic cooling it will substantially increase the need for REOs. Since there are no available numbers for these applications it is difficult to make an estimate. However, since there seems to be many new applications the need for REOs could be very large. By using REO magnets for refrigeration and cooling electricity consumption for these applications could decrease with 15 %. If REE magnets were used in air conditioning the power consumption could be reduced by 50 % (BGS, 2011). Neodymium is also used in the glass and ceramics industry even though the amount needed is not that big. Neodymium in hard disc drives is also an area of consumption which will continue to increase.

### 8.3.4 Neodymium demand

<table>
<thead>
<tr>
<th>Nd metal for vehicles [50%-70%] [tons]</th>
<th>Nd metal for wind turbines [tons]</th>
<th>Total Nd metal needed [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 500-3 500</td>
<td>2 940 – 8 820</td>
<td>5 440 – 12 320</td>
</tr>
</tbody>
</table>

**Table 19**, The amount of neodymium required for both wind turbines and electric vehicles in 2015

The current annual production is 20 490 tons of Nd. If producing 5 million vehicles by 2015 there is enough Nd to account for between 50 – 70 % of the current production. Apart from the vehicles the supply will also be enough to produce wind turbines.
In 2050 the production could be around 100 000 – 200 000 tons of Nd, while potentially 25 000 tons would be needed to power 50% of the 50 million cars with Nd. Installing 600 GW of wind power where 14% is direct driven turbines is not a problem if the production follows the prognosis. The peak production will be considerably higher as seen in (table 22).

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>17</td>
<td>37 680</td>
<td>25 170</td>
<td>32 310</td>
</tr>
<tr>
<td>30</td>
<td>38 491</td>
<td>26 237</td>
<td>34 970</td>
</tr>
</tbody>
</table>

*Table 20, Production of Nd 2015 by different models*

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>17</td>
<td>191 451</td>
<td>56 513</td>
<td>132 245</td>
</tr>
<tr>
<td>30</td>
<td>333 922</td>
<td>98 571</td>
<td>144 276</td>
</tr>
</tbody>
</table>

*Table 21, Production of Nd 2050 by different models*

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>261 973</td>
<td>84 241</td>
<td>184 426</td>
</tr>
<tr>
<td>30</td>
<td>456 923</td>
<td>146 933</td>
<td>274 279</td>
</tr>
</tbody>
</table>

*Table 22, Peak production of Nd*
9. Discussion

9.1 Lithium

It would be very useful to have the production lithium metal data instead of gross product. It is difficult to estimate the exact amount that has been extracted due to that. The data used in this report is only public free data. There are other sources, but they are made by companies and are expensive therefore they are not included here.

Seawater or lakes will not likely become a future source of lithium. The technical difficulties are extensive due to low concentrations and the therefore large volumes of water that needs to be processed. Another problem would be the inlet and outlet of the processing facility, which has to be in different regions otherwise the same water would be processed over and over again and then the concentration would be further decreased. To avoid that, long pipes have to be built for the outlet water to be transported elsewhere. The deep sea mud could potentially be a source of REE however it will most likely not become a future source of REE production in the foreseeable future since it is too far down below the sea and will be very difficult and costly to extract.

If both fusion, electric and hybrid vehicles will be built there could be a problem with the lithium supply, (see table 14). If stockpiling lithium for several years it is possible to build some fusion reactors, however installing 1000 GW of fusion power with lithium as a breeder does not seem possible. If looking into the annual consumption in fusion reactors it is possible however there are such large amounts needed when building the reactor that it seems unlikely. If half of the lithium production will be demanded for electric and hybrid vehicles and there is not that much left for fusion, unless the other current lithium applications demand will decrease drastically. The production could increase about five to ten times or more, as seen in table 15 depending on the prognosis which makes it difficult to predict the future. To make the production last longer the prognosis should follow Gompertz or Richards. The URR will probably be closer to 15 million tons than to 30 million tons.

Regarding to Gaines (2000), there will be no problem with lithium until 2050 and after then other solution are probably available then they are assuming that recycling will account for a large part of production. However the study only looks into the reserves and the batteries and no other lithium applications, for example the portable electronics or ceramics and glass applications which currently accounts for about 31 % of the production. DOE’s (2010) estimation until 2015 is that the production of LCE will meet the demand. Global demand exceeds the estimated production in 2025 but the report expects the production to increase further until 2025. If the production follows the logistic curve, it will be sufficient to 2050, if only considering increased lithium consumption for vehicles. It is not likely that the only increased demand will be for vehicles but other applications will probably have an increased demand too. It is not very reasonable to assume that there will be another solution after 2050, there might be but it is nothing that is possible to take for granted.

9.2 Neodymium

Schuler et al, (2011) stated neodymium as one of the elements with highest supply risk even if China does not decrease their export of it. Due to these calculations which cannot be very precise but just an estimate for the future there can be problems for the neodymium production to meet the demand. The reserves are quite large but there are many applications where it is advantageous to use neodymium to other elements. Since REOs exist together with radioactive elements there are large environmental problems with mining it which could decrease the production and the demand for neodymium. The
mine Mountain Pass had to close due to environmental problems and decreased prices. Perhaps the supply risk creates mines whose environmental problems are overseen by this reason. BGS (2011) predicts a production of REE outside of China in 2013 to be 130 000 tons, which would double the current production, with the assumption that China continues to produce the same amount. That estimate cannot be met based on the models used in this report. The production could increase by about 50% until 2015. Since there are so many projects about to start it could be a possibility if enough of money is invested and no other complications arrive. It is such a large and complex system that it is difficult to account for all perspectives. The peak production could be very large, see table 22, and the production could increase a lot, but not as fast as BGS (2011) and Chen (2011) estimates.

Many applications need neodymium, and the production seems to be large enough to power 50% of the potentially produced 50 million cars per year in 2050 along with some direct driven wind turbines. Portable electronics and magnetic refrigeration are not taken into consideration, which could be done in a more through report. Recycling is not considered either which it perhaps would change the results. Currently it is difficult to recycle neodymium is a problem due to its complex structure and similar properties to other REEs, furthermore it is corrosive and expensive to recycle.

The main problem with the REO production is that there is currently only one producer on the market which is China. Also, there are large reserves of REO but it takes time to increase the production due to large economic investments.

9.3 Data

The available data for neodymium reserves and production are very limited. It is difficult to do reliable forecasts based on limited data, the margins of error are quite large. It is possible to see that there are still large amount of neodymium left to be mined and it will last for some time, depending on our demand and China’s unreliable supply. It is an element which could quickly become unavailable due to those factors. The data for the Chinese production varies, especially the production numbers which comes from China. The official production is reported, however, there is still a large amount of unofficial and illegal production in China. The unofficial production is decreasing as seen in figure 21, but it is still a problem. Since some production is illegal it can be even more difficult to estimate the reserves and resources of the available amount. Also, the data estimations for neodymium content in applications are inadequate. One example is whether the estimation is based on neodymium or neodymium oxide. The estimations for vehicles do not specify whether the estimate is for the battery, a permanent magnet in the car or both.

A large problem is that resources and reserves are quite often mixed up in articles. That makes it even harder to estimate the actual amount of resources and reserves. One example is Falås (2010) who states that the availability of lithium will not be a problem since it is estimated to be 35 million tons. One Li-ion battery with a capacity of 20 kWh needs about 3 kg of lithium, so the amount of batteries that could be produced is 11 million. They probably assume that the reserves that are 35 million tons, which is possible, however most sources states them as lower than 35 million tons. The current estimation is that the reserves are 15 million tons and the resources are 30 million tons. It is not reasonable to use all the lithium for batteries for vehicles but the industry also demands lithium to glass and ceramics.

The mean lithium concentration calculated from both BGS and USGS’s series is about 6% of the grossproduct. However, the concentration is decreasing and thereby the cost for extracting the lithium is increasing, (see eq 2). When the concentration is decreasing more waste material has to be mined to produce the same amount of metal. An example of that is figure 17, where lithium gross product and
lithium metal is plotted, it can be seen that the amount of gross product has to increase much more than the metal content. Waste rock is a large problem in the mining industry, it occupies large areas. That is another restriction that is not accounted for in the model and which could decrease the reserves.

It is difficult to estimate the reserves since they are dynamic and are changing depending on many factors such as technology, price, social, political factors and environmental factors. It is not possible to account for these factors when doing the curve fitting, so they are not taken into account. They should still be discussed. If using the logistic model it is to say that the market is free and there are no economic limitations. Using Gompertz or Richards models, which have limitations is probably a more realistic model due to its slower decline, which would be a more sustainable production pattern, and could be restrained by a low depletion rate. It is not possible to determine the future and therefore good to have different models which show different scenarios.

The production data include other errors, some countries are not included in some data and other countries are not included in other data. The U.S does not report their lithium production, however lithium is probably not produced in large quantities in the U.S since their reserves are 38 000 tons. However, BGS has estimates of the U.S data, but other data is missing from their report. A more objective and correct report on the data would be very interesting to have.
10. Conclusions

A new worldwide system should be introduced for estimating mineral reserves and resources. For example NI 43-101 could be used more frequently to make the estimations more consistent with each other. The lack of data is a problem, and the data used in this report is only public free data. There are other sources, but they are made by companies and are expensive, therefore they are not included here. To make a good investigation it is important to have as much and accurate information as possible, but sadly the current situation leaves much to desire.

There are other problems with the distribution of reserves, being dependent on one or a few countries makes the market unsecure. Especially for REOs, however more mines are opening the next years so China’s domination of the REO production could decrease. It is an energy security question as DOE and the European Commission have expressed concerns for. The lithium production is less concentrated, but it is mainly provided by four countries and could also cause concern according to DOE.

There are large reserves of both lithium and REOs but it takes time to increase the production due to large economic investments. Lithium in seawater will probably not become a source of lithium in the near future. If recycling was both commercialized and widespread the availability would be less of a problem. Currently it is not possible to count on recycling to be a large part of the production. Both lithium and neodymium (REE) can be exchanged to other materials however the efficiency will be decreased.

The URR mainly affect the production capacity, not the particularly peak year/peak decade. The prognoses with the lower URR are the most realistic ones, due to factors such as decreased concentration and a more sustainable use of minerals. The lithium production can power at least 5 million cars with lithium ion batteries until 2015 without any problem. However if prognosis such as IEA’s that 50 million electric and hybrid cars will be sold annually by 2050 cannot be met by only using lithium batteries with current technology. Fusion with lithium as a breeder cannot be done in a large commercial and global scale using the current technique. The reserves of lithium are too limited and other applications such as batteries and the glass and ceramics industry also needs their share of the production.

The production of neodymium will be large enough to produce 5 million vehicles with neodymium magnets and NiMH batteries until 2015. Furthermore the production is also sufficient to produce 50 million vehicles per year and to have about 14% of direct driven wind turbines in 2050. The future need of permanent magnets in electronics will probably increase and that is not included in my calculation. With that in mind the neodymium production could potentially be a problem. All wind turbines cannot be direct driven, the neodymium reserves are too limited, however a share of the turbines could be direct driven. It would require 31 500 tons of neodymium to install 300 GW by 2015, that number is larger than the current neodymium production. It is not likely that all the turbines installed by 2015 are direct driven. Perhaps off-shore wind turbines could be direct driven to decrease maintenance costs.

10.1 Future research

A lot of further work could be done in this area. REO are mainly mined as a co- or by-products. The availability of the main product has to be investigated and after that the total amount of reserves of REO could be decided, the REO reserves depends on the reserves of the main product. That could be a future project to investigate. The current status of the potential REO projects should also be further investigated and could be included in future work in this area.
According to these models, where only geological occurrence is a limiting factor it is not possible to produce enough lithium to make as many electric and hybrid cars as demanded. These prognoses are long term trends and therefore the production can fluctuate around the trend. Restricting factors are, economy and the available amount of factories which can produce the demanded amount both batteries and permanent magnets. That is something to look into more in detail in the future to be able to do better and more reliable prognoses. It is possible to look into fusion more in detail to estimate how much lithium that is needed in a fusion reactor, how large the blanket would need to be. Batteries could perhaps be made more efficient in the future, which would require less lithium, which is another thing to investigate. Energy security could also be further researched since only a few countries stand for most of the production of both metals political problems could arise due to that fact. China’s export quotas are an example of an already existing political problem.

All together more data and more precise prognoses could be made but by this start it is an interesting area to research. Since only availability is taken into account it is probably not possible to produce as much as the curves are anticipating due to economic and social factors. The minerals are finite and before the transport sector are electrified and we build our society on permanent magnets it is important to know whether it is possible to turn from oil to salt and minerals.
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Hanna Vikström, 2012-02-05
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