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Challenge the future

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Potential for Rare Earth Deposits in the Deep-Sea Environment

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Abstract

Because of high resource prices for rare earth elements over the last decade, companies and governments are investing in research in finding new deposits and innovations. The purpose of this thesis is to measure the potential of rare earth deposits in the deep-sea environment. This is done by a wide and extensive literature study with a focus on supply and demand, combined with several cash flow analyses. Some research will be on alternatives for deep-sea mining; for example recycling and substitution of rare earth elements. Obstacles like the public opinion and the United Nations Convention on the Law of the Sea, which can square up the potential, will be discussed as well.

This thesis shows that conventional mining methods can answer to the world demand for the next 40 years. Nations with high demand, but without resources, can also be supplied for the upcoming 30 years. On top of this, cash flow analyses show that mining of rare earth deposits in the deep-sea environment will not be economically feasible in the foreseeable future. Also, the ecology of the deep-sea is unique and is already starting a public debate. Furthermore, it is almost impossible to start mining in international waters, as the United Nations Convention of the Law on the Sea prohibits this.

Although recycling and substitution developments are in their infancy, nations and mining companies invest in these alternative methods. It is more likely for nations to continue to invest in these technologies rather than deep-sea mining.

All-in-all it can be concluded that the potential of rare earth deposits in the deep-sea environment will be extremely low during the upcoming decades.

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1. Introduction

This thesis will measure the potential of rare earth elements in the deep-sea environment. The main focus is the market and the economic feasibility.

First I will illustrate the technical possibilities of rare earth elements (REE) and the rarity of deposits with an abundance that is high enough to make it become economically feasible to be mined. This section is needed to understand what the market is based on. It affects the development of the supply & demand of REE and it is important to determine the economic feasibility of the deposits.

Next, the demand will be discussed. At the end I will give a prediction on the growth of the demand during the upcoming decades. This chapter will show the first effects that could influence the potential of deep-sea mining, both positively and negatively.

After discussing the demand, the following topic will be supply. Can the world supply accommodate the world demand? A few scenarios and possible price developments can be envisaged.

Because the economic feasibility of deep-sea mining will be decisive, I did a few cash flow analyses for different mines and for a deep-sea deposit. Together with recognized price influences from earlier chapters, the potential of deep-see mining for REE can be measured in economic terms.

In the end there are always a few obstacles that could influence the potential of deep-sea deposits negatively. One should think of recycling, substitutions or a blockage because of a negative public opinion.

As a final conclusion I measured the potential of rare earth deposits in the deep-sea environment.

2. Background

Elements

For an engineer with a chemical or geological background it will sound familiar. But for the common reader I will write it again.

"Rare Earth Elements are neither rare, nor earth elements."

In the early discoveries of the elements group, it was presumed that the elements had a rare presence in the Earth's crust. But nowadays it is well known that the elements are very common. Cerium, the most common element, is the element with the 25th highest presence. It is more common than lead. The least present rare earth element is still more common than gold. However, the elements may not be rare, deposits with an abundance that is high enough to make it become economically feasible to mine are certainly rare.

The second misunderstanding is explainable by the French word 'terre'. Nowadays it means 'earth', but in the 19th century it also stood for 'oxide'. And because of the fast oxidation of REE, that word was right in place.

The group Rare Earth Elements (REE) exists of 17 elements. 15 of those 17 elements are Lanthanides and exist of Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb) and Lutetium (Lu). Besides those 15 elements the two elements Scandium (Sc) and Yttrium (Y) are also considered as REE.

Scandium (Sc) is a very soft and light metal with a relatively high melting point, higher than aluminium. The spacecraft industry is interesting in this element because of the high melting point. But the costs of using Scandium is high, so it is less used. Furthermore it is used in the production of high-intensity lights.

Yttrium (Y) is a lustrous and silvery metal and is often used to increase the strengths of aluminium and magnesium alloys. Furthermore it is used in high-temperature superconductors and in phosphors used to provide the color red in TV tubes. Its radioactive isotope is used in cancer treatment.

Lanthanum (La) is one of the rare metals that is so soft it can be cut with a knife. This silvery, white element is one of the highest reactive metals that directly reacts with halogens, but also with elementals such as nitrogen or sulphur. In large quantities this REE is used in batteries for hybrid vehicles, e.g. a Toyota Prius battery requires about 10 kg of lanthanum. Furthermore lanthanum is used for camera and telescope.

Cerium (Ce) is considered to be the most abundant of all REE's. This ductile grey metal oxidizes very quickly at room temperature and is also highly reactive. Misch-metal (cerium-lanthanum alloy with neodymium and praseodymium) is used in cigarette lighters when combined with iron and magnesium oxides. Cerium-oxide is considered one of the best glass polishers and is also used in polishing quartz, agate, opal etc.

Praseodymium (Pr) is a soft and malleable and a bit more resistant to corrosives than most of the REE's. Its oxide is one of the most refractory substances in the world. Together with other REE's it is applied in carbon arcs mainly used for studio lighting and projection in film industry. Furthermore praseodymium is used in high-intensity permanent magnets, which are essential in electric motors and generators used in hybrid cars and wind turbines. Praseodymium is also used in nickel metal hydride (NiMH) rechargeable batteries for hybrid automobiles. The negative electrode (cathode) in NiMH batteries is a mixture of metal hydrides – typically a rare earth misch metal hydride containing praseodymium, neodymium, lanthanum and cerium.

Neodymium (Nd) is another metal that is present in Misch-metal and is so up to 18%. It is a silvery lustrous element, which is among the more reactive REE's. It is used in colouring glass and is further applied in astronomical works, as well as in producing coherent light in lasers. Neodymium is further used with iron and boron to create powerful permanent magnets, also called $Nd_2Fe_{14}B$ magnets. $Nd_2Fe_{14}B$ magnets are used in computers, cell phones, medical equipment, toys, motors, wind turbines and audio systems.

Promethium (Pm) is a radioactive element which requires careful handling. In the dark, its salts luminescence in green and blue colors. It is used for the conversion of light into electricity and has the potential to be used as a portable X-ray unit. It is also used as a power source for solar semiconductor batteries.

Samarium (Sm) is a bright silver metal used, as some of the other lanthanides, in carbon arcs lightings for the motion picture industry. Its oxide is used as an infrared absorber in optical glasses as well as neutron absorber in nuclear reactors. Since the 1970's it had been used in the production of samarium-cobalt magnets, a permanent magnet. These magnets have a high resistance to demagnetization. They keep their ferromagnetism at temperatures up to 700 ˚C. As a result of their ability to operate at high temperatures, samarium-cobalt magnets are used in precision-guided weapons. Radioactive ^{153}Sm is used in the treatment of cancers.

Europium (Eu) is one of the most reactive REE's which quickly oxidizes. As its isotopes are good neutron absorbers, europium is used in nuclear control applications. Further it is used as an activator in substances crucial for the production of TV tubes. Europium is also used in phosphors in anti-forgery marks on Euro bank notes.

Gadolinium (Gd) is known for its use in microwave applications as well as in phosphors used in TV tubes. This shiny silvery metal is also the element with the highest known thermal neutron capture cross-section.

Terbium (Tb) is another gray metal soft enough to be cut with a knife. It is used in green phosphorus in TV tubes. Tb^{3+} ions can be used to check for the presence of microbes. Terbium chloride is applied to the test area, which is then illuminated with UV light. Within minutes, any live endospores present will glow green. Euro banknotes use rare earth chemistry to defeat counterfeiters. Shining UV light on a banknote results in green.

Dysprosium (Dy) has a metallic lustre and a relatively low reactivity when compared to most of the lanthanides. However, even small impurities can severely affect its physical properties. It has potential to be used in nuclear applications and it has been applied, with vanadium, in laser production.

Holmium (Ho) is a silvery metal that quickly oxidizes when exposed to high temperatures and a moist environment. There are not many uses known apart from the usual application of REE's in alloys.

Erbium (Er) in air oxidizes slower than most REE's. As with some other metals from the group, its physical properties are sensitive to impurities. The main applications of erbium are in the nuclear and metallurgical industry. When combined with vanadium, this metal tends to decrease the hardness of the alloy and make it more workable.

Thulium (Tm) is a silver-gray metal of great softness. As it is relatively highly priced on the market, its practical applications are almost negligible but, just as promethium, it is considered to be of potential use as a portable X-ray unit. Thulium is also used in euro banknotes for its blue fluorescence under UV light to defeat counterfeiters.

Ytterbium (Yb) is a very soft, malleable and ductile element. Its main uses are in alloys (stainless steel) and lasers but one of its isotopes is also used as a radiation source for portable X-ray units when there is no electricity.

Lutetium (Lu) is probably the most expensive of all REE's as it is present in only small amounts (usually accompanies yttrium) and very difficult to extract. Its nuclides can be used as catalyst in various process, including polymerization and hydrogenation. Lutetium oxyorthosilicate (LSO) is currently used in detectors in positron emission tomography (PET). This is a noninvasive medical scan that creates a three-dimensional image of the body's cellular activity.

The REE can be found in approximately 200 minerals. The most important REE-minerals are monazite, bastnaesite and xenotime. As I told in the start, the elements pure will oxidize fast and when oxidized, the rare earth elements become rare earth oxides (REO). The metals are mostly mined as monazite and bastnaesite.

(Chemicool, 2013)
(HCSS, 2010)
(Voncken and Wolf, 2011)

Chemical properties

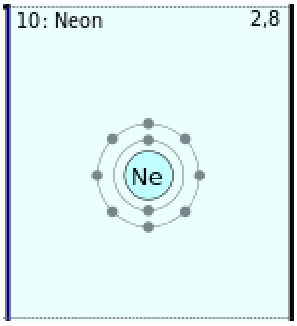


Figure 1: A Neon atom with 10 electrons distributed over two shells.

What makes these elements so special? An answer for this can be found in the electron configuration. All the electrons of an atom are distributed over several shells around the atom. The shell closest to the nucleus holds maximum 2 electrons, the shell second closest holds a maximum of 8. The third and fourth are holding respectively 10 and 18 electrons. Shells on more distance from the nucleus have all a max of 32 electrons. The way the electrons are distributed over the shells is important for the chemical properties. For example neon, this noble gas has 10 protons and therefore it needs 10 electrons. And with 10 electrons the atom can fill up both two closest shells and extra important is the outer shell what defines many of the properties (Figure 1). Because the outer shell is completely filled, the atom is in a perfect energy state, is therefore stable and is hard to break. In this way of thinking there are 5 more noble gasses and because of this distribution these elements share the same properties. And because of the optimal energy state and the low reactivity of a noble gas, every other element aims to get an electron configuration that's looks like the one from a noble gas.

For the rare earth elements, or the Lanthanide-group, it is a bit more complicated. In this group the first three shells are filled, the fourth is partly filled and there are a few electrons holding out in the fifth and sixth shell (Figure 2). For every element that has a proton more, the fourth shell will be further filled. The largest element, lutetium, has a filled fourth shell. And because the fourth shell is not the outer shell, the elements have the same kind of properties. As said before, all elements want to look like a noble gas, these elements want to look like the noble gas xenon. By losing the outer two or three electrons in bonds with other elements they succeed.

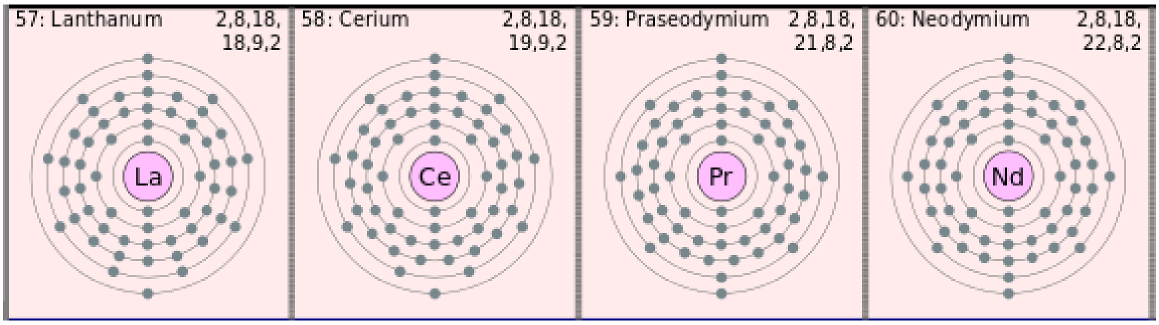


Figure 2: The electron configurations of La, Ce, Pr and Nd. The outer shells have always respectively 8 or 9 and 2 electrons.

There has to be said that this is a simplified explanation and the detailed explanation is much more complicated.

Geology

To discuss the future role of Rare Earth Elements, it is important to understand the geology behind the deposits. Rare Earth deposits are unusual and have many limitations. The most important deposits are here explained.

Onshore Deposits

Alkaline Rocks

The most rare earth deposits are (per)alkaline rocks. The formation of alkaline rocks is complex, but the most important mechanism is 'fractional crystallization of magma'. This means that the magma, in this case REE containing magma, doesn't crystallize uniformly during the cooling. During the crystallization of fractions, the crystals sink down and the REE concentration of the liquid becomes denser. This results in a rare alkaline magma with unusually high concentrations of REE. The REE containing alkaline rocks are mostly carbonatites. To illustrate how uncommon carbonatites are, the volcano 'Ol Doinyo Lengai' in Tanzania is the world's only active carbonatite volcano. Famous examples for REE carbonatite deposits are Bayan Obo, Mount Weld and Mountain Pass in respectively China, Australia and USA.

Placer Deposits

Another important deposit are placer deposits. These deposits are formed by the sedimentation of eroded material of all kind of rocks. This process concentrates denser minerals, in this case the REE minerals, into deposits known as placers. Many common igneous, metamorphic and even older sedimentary rocks contain monazite. As a result monazite can be found in almost any placer. But economically amounts of REE are mostly found in ilmenite containing placers.

Hydrothermal Deposits

Hydrothermal deposits are formed by warm acidic water that flows through the formation. Small amounts of REE are dissolved by the water and are transported to and deposited on another location. It has to be said that in order to reach minable levels the source rock already needs high concentrations of REE. Hydrothermal deposits mostly contain LREE.

Laterites

High temperatures and humid air in the tropics could cause deep weathering of rocks at the surface. A good example are the red soils in Australia and Africa. Hereby the source contained high concentrations of iron. The source rock is weathered and turned in to clayey soils. When leaching occurs, the soil will separate in zones with different chemistry and this results in an enriched-iron layer over the underlying, unweathered rock and because of the (oxidized) iron, it has a red colour. Conform this example, the same could happen with REE bearing source rock. However, these deposits are rare and the only known are located in southern China and Kazakhstan.

Marine Deposits

Guyot

These are old volcanic plateaus beneath sea-level. The formation of these plateaus are similar with the formation of alkaline rocks. When the volcano became inactive, the sea eroded the top part of the volcano. The result is a plateau under sea that is sometimes more than 2000 meters above the seafloor and only a few hundreds of meters below sea-level. Detailed information about these deposits is rare. However according to Julie J. Dieu (1995) several guyots contain small amounts of rare earth elements. Because guyots have the same origin of basic igneous rocks the concentration of REE is variable and there could be guyots with relative high concentrations. And because of the modest depth, these deposits could be promising for in the future.

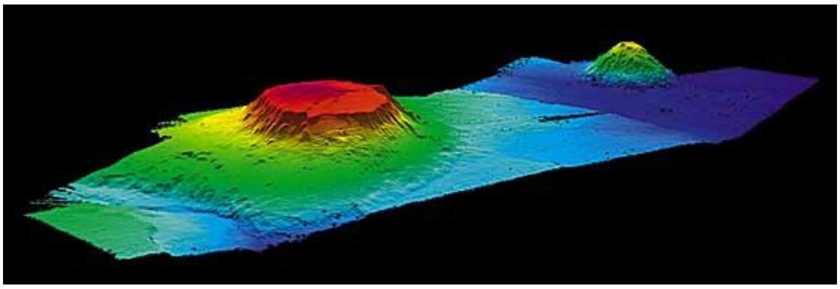


Figure 3: Bear Seamount, a guyot in the North Atlantic Ocean

It is estimated that in the Pacific Ocean, there are over 30.000 estimated seamounts. In the Atlantic Ocean and the Indian Ocean the seafloor is less mapped, but there are low expectations for these areas. *(Iyer et al. 2012)*

Hydrothermal Vents

Near volcanic active regions like hot spots and mid-ocean ridges, local water is warmed up and because of the created overpressure it burst out of pipes or fissures. The most famous example is the geyser. In the case of hydrothermal vents in the deep sea the properties are a bit more extreme. Because of the water column of 2000 to 3000 meter there already is a pressure of 200 to 300 atmosphere at the bottom of the ocean. The water is warmed up to sometimes more than 400˚C. Under these conditions the water is far above its critical point. It moves like gas between the pores en through the pipes and it dissolves minerals like a liquid. Once out of the vent water cools off to beneath 10˚C and the minerals are precipitated. The most famous example are the black smokers.

Hydrothermal Vents are promising deposits, but just like any other deposit it does not mean that every hydrothermally vent produces REE bearing deposits. For example the largest deposit of hydrothermally precipitated metals on the present ocean floor, located on the Red Sea rift axis, doesn't contain REE concentrations that are economically mineable. *(Laurila et al., 2013*

Deep Sea Muds

Recent research *(Kato, 2011)* has showed us that these deposits in the Pacific Ocean are enriched with many REE. The source of these elements are mostly hydrothermal. The average amount of TREE is comparable or greater than those in China. However for the HREE, those averages are twice that high. Furthermore these deposits are enriched with V, Co, Ni, Cu, Zn, Mo and Mn, these concentrations are also twice that high and all of them economically valuable. On top of that the amount of radioactive elements thorium and uranium are relative small. Ironic is that all limitations of onshore deposits seem not applicable to these deposits. Nevertheless these deposits are on a depth of more than 2000 meters, which is a huge limitation on its own.

Manganese Nodules

Due to precipitation of dissolved metals onto small fragments rock concretions are formed. These dissolved metals could origin from hydrothermal vents, from the underlying rock or through active micro-organism. The classical form of the nodules is because of the erosion that takes place after rolling over the seafloor. The formation of those deposits is very slow. It takes one million years to get a nodule with a diameter of 1 cm. The concentrations of REE in nodules are similar with the original concentration in sea water, this is because of the source of metals is the sea water itself. The result of this is that the nodules are economically less interesting with regards the REE. But there are a few exceptions. Depending on the environment CeO_2 could replace MnO_2 in the nodules (*Goldberg and Koide, 1963)*, which is resulting in a relative high Ce-containing nodule. In another environment the present europium or samarium in the underlying seafloor could be replaced by calcium. The effect of this, are high concentrations of Eu and Sm in the sea water and therefore also in the nodules. *(Goldberg and Koide, 1963)* So manganese nodules are in the case of REE less interesting, but besides the exceptions the nodules still contain high concentration of economically interesting metals. Especially this last advantage of the nodules has made a multinational group of USA, Canada, Japan and several European countries invest in deep-sea mining during a short period in the seventies and still there are a few companies, like Nautilus Minerals, active. Maybe these deposits are less interesting for the REE production, their technology could be very important for the future deep sea mining of REE deposits.

Short Conclusions

It should be clear now that the elements group has given a high contribution to the high-tech industry. Because of the specific properties of the elements, which is making them so effective, it could be hard to find alternatives. And that makes the elements wanted by the industry. But finding these elements is not that easy. The geological processes have spread even the most common rare earth element, cerium, out over the world. And when there are high concentrations of REE present, then nature found a way to make it difficult to mine or process them. The result is that the rare earth industry is a challenging market with a growing demand, and a supply chain, we can't always rely on.

3. Demand

Current situation

As can be seen in the description of each of the elements, these elements are mostly used in high forms of technique. The rare earth elements are mostly used in mature markets, such as catalyst, glassmaking, lighting and metallurgy, which account for 59 percent of the total worldwide consumption. These are markets that are growing at the rate of the growth for the general economy. The other 41 percent is used in newer and high growth markets, such as battery alloys, ceramics and permanent magnets. These markets grow at 4 to 10 percent per year. *(USGS, by Thomas G. Goonan, 2011)*

The general economy is growing over the last decade around 3,7 percent. As can be seen in Figure 4 the growth rate of worldwide gross domestic product (GDP) is 'stable' around the 4 percent, with an exception for 2009, this because of the crisis. *(Index Mundi, 2013)* The GDP is an indicator of the country's standard of living. Under economic theory, GDP per capita exactly equals the gross domestic income (GDI) per capita. This means that the mature markets have a growth rate of 3,7 percent.

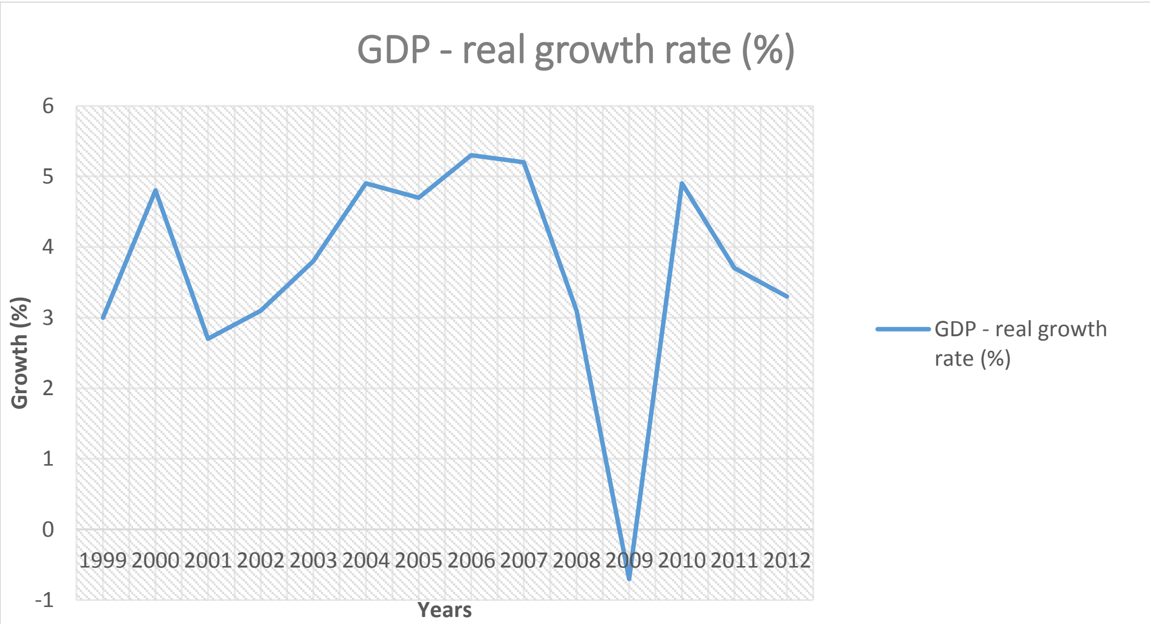


Figure 4: The real growth rate of the worldwide Gross Domestic Product (GDP) over the last 14 years. (indexmundi.com and CIA World Factbook, 2013)

This percentage is that high because of the high growth of non-western countries. Poland is the highest rated western country on that list, with a rate of 4,4% it is placed on nr 85 and together with Sweden, those are the two only western countries that are placed in the top 100. *(Index Mundi, GDP – real growth rate per country).* And what about the BRIC's[1]? China is growing with a rate of 9.2%, India with 7.2%, Russia has a rate of 4.3% and for Brazil the value is 2.7%. There is a rise of the BRIC's expected and covering 2,5 billion people in the world these percentages are an important factor to take in account. So it can be said that even when the economy in western countries is stabilized, the mature markets still continued to grow, with thanks to the third world and the rise of the BRIC's.

Because of the higher standard of living in the rest of the world and the upcoming of newer markets, worldwide consumption grew from around 60 thousand metric tons in 1994 to 130 thousand metric tons in 2009 (Figure 5**Fout! Verwijzingsbron niet gevonden.**). *(USGS, 1996-2013)* In the period of 1990

[1]Brazil, Russia, India and China

till the crisis in 2007 the annual growth was 7%, after 2007 demand temporarily stabilized or dropped a little. *(Goonan, 2011)* At the end of the line the world mine production was almost equal to that of the world global demand, see chapter 'Supply'. *(Long, 2011; Great Western Minerals Group, 2010)*

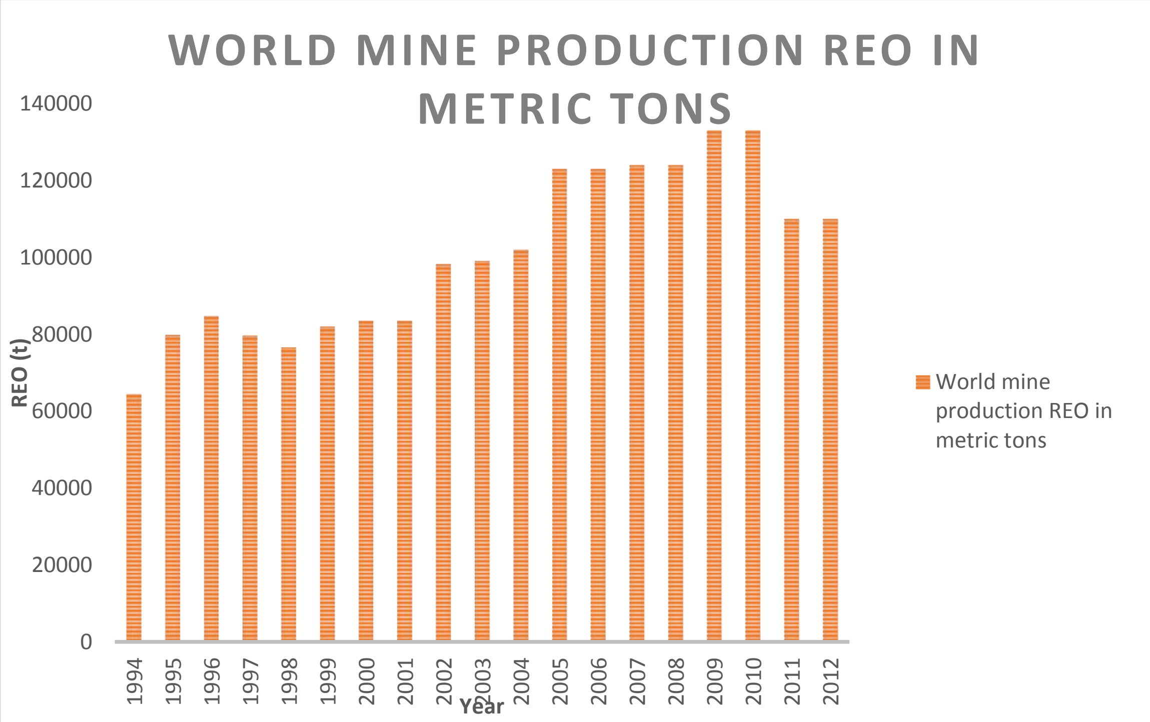


Figure 5: Annual publications of the Mineral Commodity Summaries for rare earths by the USGS. The numbers for 2012 were an expectation.

Expectation

There are a few factors left which we must take in account. The first one is the growth of the world population. The next 40 years the world population will grow from 7 billion to 9 billion people. The top will be reached near 2075 with 9,5 billion people. *(NATO, Bevolkingsgroei: de allesbepalende uitdaging van de 21ste eeuw , 2011)* And as said before the standard of living of those 9 billion people will also rise. Furthermore the expectation is that the substantial growth will continue as new applications and discoveries are made. Thereby only a few rare-earth applications will be substituted, most will not. *(Hedrick, 2010)*

The short term expectation is that the growth of the Rare Earths demand will rise again to 170.000 a 190.000 metric tons in 2014 and to even 190.000 a 210.000 metric tons in 2015 and 2016. *(Long, 2011)*. Furthermore there is a forecast for each of the 17 elements for the years 2015 and 2020. *(Ernst & Young, 2011)*. This forecast is focussed on the shortage and excess of each of the elements. It shows that there will be a shortage of 1,000 REO tonnes of dysprosium, europium, terbium and yttrium. For neodymium there will be an even bigger shortage of 7,500 REO tonnes in 2015 and 17,500 REO tonnes in 2020. These elements could solely influence the developments within the rare earth industry.

The long term expectation goes to 2064 (50 years ahead) and is based on the last century's growth in demand, the growth in world population and the growth of the GDP. A straight line forecast with an optimistic 7% growth is 5 million tons by 2062. But there is also a chance that the 'technological revolution is decelerating. For a less optimistic forecast with 5% growth, the demand is only 2 million tons. In the case of acceleration of the growth, let's say 10%, the demand will be 20 million tons of

REO. Convert these predictions into a prediction of the cumulative consumption for the next 50 years and we get Figure 6.

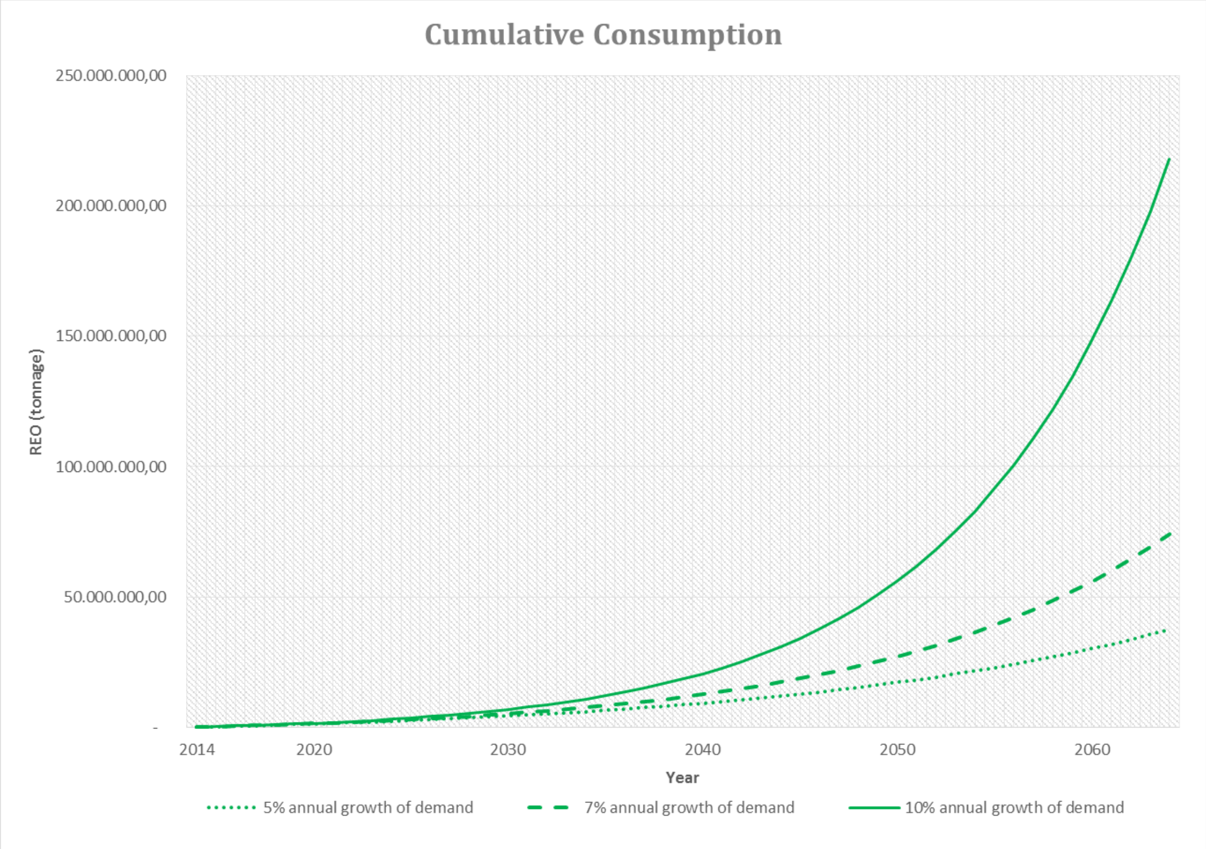


Figure 6: Three different scenarios for the cumulative consumption for the next 50 years.

Key Consumers

China is the main producer (97% in 2009) of the REE, more about that in the chapter 'Supply', but China is also the main consumer of the REE. 60 percent of all the REE's goes or stays in China (Polinares, 2012). This is a very high number for a country with 1/7th of the world's population. There are a few possible explanations. The first one is that China is more eager to sell secondary products, because of the higher value of those. Another explanation is that China is realizing the possible shortages in the future and together with the technological revolution at the moment they are stockpiling rare earth oxides. The final explanation is that China is using their monopoly position to push up the prices and sell it for maximum. But this had a reverse effect: other countries started producing, and this lowered the price.

The second largest consumer is, with all its high-tech industry, Japan. 15 percent of the REE's goes to Japan and that is quite a high number for a country where REE don't occur. *(IHS, 2013)*

Country/Region	Share [%] *(Polinares, 2012)*
China	60
Japan & SE Asia	20
USA	12
Others (incl. Europe)	8

Table 1: Consumers of REE's.

Short Conclusion

It seems that the demand depends on steady factors. Except for the technical developments, the other factors are quite stable. But the continuation of the exceptional high growth in the new industries is less certain. But if it does, the curve of the demand expectation (**Fout! Verwijzingsbron niet gevonden.**) is alarming. As I told in the chapter 'Geology', economic feasible deposits are rare and so this raises the question: could the world supply answer to the potentially high demand in the future?

Furthermore there a few parts in the world with solely a high demand for REE. These nations need to watch out, because just like Japan, Europe doesn't own many REE deposits. So for the industries in Japan and Europe the REE import is quite important. Especially for them it is interesting to search for alternatives for REE or to make an alternative policy.

4. Supply

Current Key Producers

Until 1984 the most of the total Rare Earth Oxides (REO) were mined in the USA. Specificant this was in the Mountain Pass mine in California. For 15 years the mine mostly maintained the production on the same level. After 1984 the production in China came up and eventually the so called Chinese era started in the early 90's with 30-40% of the world supply mined in China. (Figure 7)

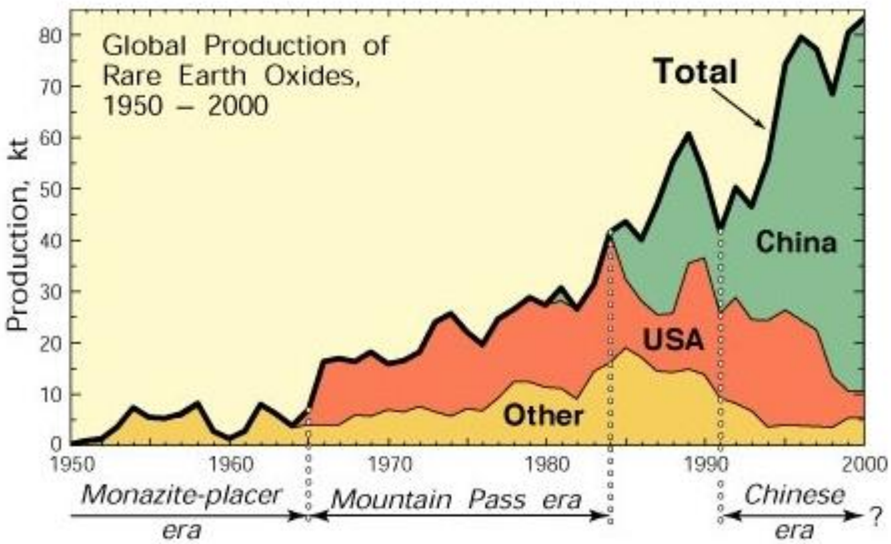


Figure 7: Global Production of REO, 1950-2000.

China was selling rare earth for low prices, so the mining production in other countries was uneconomic, together with environmental reasons this lead to the closure of mines, including the Mountain Pass mine in 2002. In 2009 the share in production of China was 97%. *(Polinares, 2012)*.

Country/Region	t REO	Share [%]
China	129.400	97
USA (stockpiled concentrates of Mt Pass)	1.900	1.4
Russia	1.898	1.4
India (estimated, stockpiled monazite)	35	<0.1

Table 2: World production in 2009.

In China there are about 24 mining companies, of which Baotou Iron and Steel and Rare Earth Co. is the biggest. It produces 40% of the world production. Minmetals Ganzhou Rare Earth Co. Ltd. is producing 25% of the world production and is good for a second place. Furthermore China owns the most advanced rare earth separation and smelting technology in the world. It is the only country in the world that can provide rare earth products of all grades and specifications. Outside of China there are only a few 'important' mining companies with Molycorp Minerals LLC on the lead (1.4%) and other companies involving rare earths are mainly involved in manufacturing processes for (semi-) finished product which contain REE. *(Polinaris, 2012)*

Rare Earth Crisis

In 2006 China started to restrict the rare earth exports by export quotas. Between 2007 and 2010 export quotas were reduced by 56%. This resulted in increasing prices for all the REE. But in 2008 the prices dropped due to the global financial crisis. After the crisis the prices started to increase again and reached records high at the middle of 2011. Some of the rare earth elements reached ten times as high as a year earlier. Besides the Chinese restrictions, the concern for supply shortages was also a reason for this. *(Polinaris, 2012)*

The crisis alerted the rest of the world. It started the search for new rare earth oxide deposits and old mines became economic interesting again. But still, the rest of the world has an huge disadvantage on China concerning the technological possibilities.

Follow-up of the crisis

The crisis had caused a boost into the REO industry and within a few years the number of operating mines doubled. At this moment there are eleven mines active or ready to start this year. The US Geological Service, Geoscience Australia and Polinares *'EU Policy on Natural Resources'* have published over the last years several reports about all the active mines, resources and reserves. These information combined and checked with annual reports of active mining operators lead me to recognize the following development.

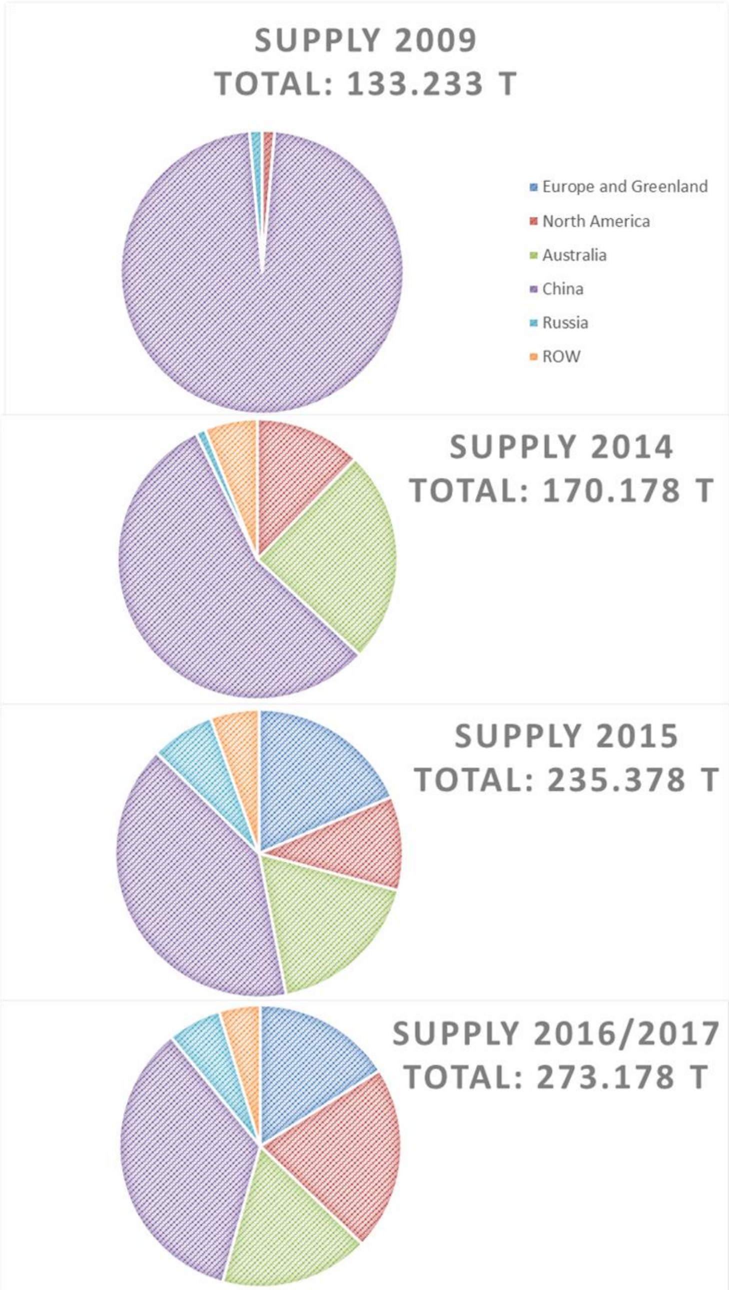


Figure 8: Development of the world supply between 2009 and 2017.

As can be seen in Figure 8 the world production was dominated by China in 2009. In 2014 the world had showed a fast and effective reaction on the REE-crisis. Only in a few years the production levels outside of China grew from a few thousands of tons to several tens of thousands tons of TREO. Also the short term future shows a steady growth in production. and the expectation is that the production-share of China will drop further to 35% in 2017.

Also the location of the mines is favourable for the next decade(s). Most of them are located in western countries as Canada, the USA and Greenland. Especially the last one is promising with an enormous potential of TREO. In Appendix A you can find a complete overview of active mines and deposits.

For a long term view on the world production, we need to look at resources and reserves.

Resources

All three geological institutes take different standards to complete their information. Result of this is huge difference between Geoscience Australia, USGS and Polinares. The information from USGS is incomplete, because China is excluded from these figures and there is no information of Russia, apart from the Lovozero mining complex. Furthermore the figures for reserves are included in the figures of resource by Geoscience Australia (GA).

Resources (t TREO)			
Country	USGS (2011)	GA (2012)	Polinares (2011)
Africa	N/A	N/A	2.370.000
Australia	1.588.000	1.650.000	4.500.000
Canada	8.083.000	N/A	N/A
China	N/A	36.000.000	66.400.000
Greenland	875.000	N/A	10.400.000
Other Asia	N/A	N/A	7.300.000
Russia*	1.700.000	19.000.000	166.100.000
South America	N/A	N/A	16.380.000
USA	589.000	13.000.000	4.200.000
Other Countries	1.580.000	25.588.000	1.300.000
Total	N/A	95.238.000	285.404.000

Table 3: Resource estimation by 3 different institutions. *Included Commonwealth of Independent States.

Besides the just described resources. There are also a few estimations of marine resources. In 2011 'Nature Geoscience' published an article from the University of Tokyo. They researched drill samples, obtained from the Ocean Drilling Program. For the Eastern South and the Central North Pacific they gave an estimation with a relatively high certainty and for the total Pacific Ocean they gave a rough estimation.

Region	Resources (t REO)
Eastern South Pacific	9.110 ± 1.460
Central North Pacific	25.000 ± 4.000
Pacific Ocean	110.000.000

Table 4: Resource estimation for the Pacific Ocean. (Kato, 2011)

Reserves

The same as the resource numbers, these figures are spread out. Because the reserve figures from Geoscience Australia were included in the resource numbers, the total reserves has to be lower than 95 million t.

Reserves (t TREO)			
Country	USGS (2013)	GA (2012)*	Polinares (2011)
Africa	N/A	N/A	30.000
Australia	1.600.000	N/A	1.600.000
Brazil	36.000	N/A	N/A
China	55.000.000	N/A	18.400.000
Malaysia/India	3.130.000	N/A	N/A
Other Asia	N/A	N/A	4.000.000
Russia**	N/A	N/A	3.300.000
South America	N/A	N/A	20.000

USA	13.000.000	N/A	1.100.000
Other Countries	41.000.000	N/A	0
Total	110.000.000	N/A	28.300.000

Table 5: Reserves estimation by 3 different institutions. *Geoscience Australia did nog publish specific reserve data. **Included Commonwealth of Independent States.

Although the numbers of western countries as USA, Canada or Greenland are not always the same as given by involved companies, there is more certainty to assume these numbers are correct than those from China or Russia.

Short Conclusions

Can the world supply answer to the world demand in the long term future? That was the question after chapter 3, Demand. So let's plot the cumulative demand and the supply versus the time. For the cumulative concumptions I created three different scenarios in Chapter 3, expectations. For the resources and the reserves, I used the estimations of the USGS & GA and of Polinares. All these assumption are used as constants over time. In reality they would be time and economically dependable factors. Because of the detailed separation of resources and reserves by Polinares, I could split these numbers in the graphic. Furthermore I made two lines where by the resource estimation of the Pacific Ocean was added to the other resource estimations. The result is Figure 9, which is shown in what year, which expectation passes by a specific resource/reserve estimation.

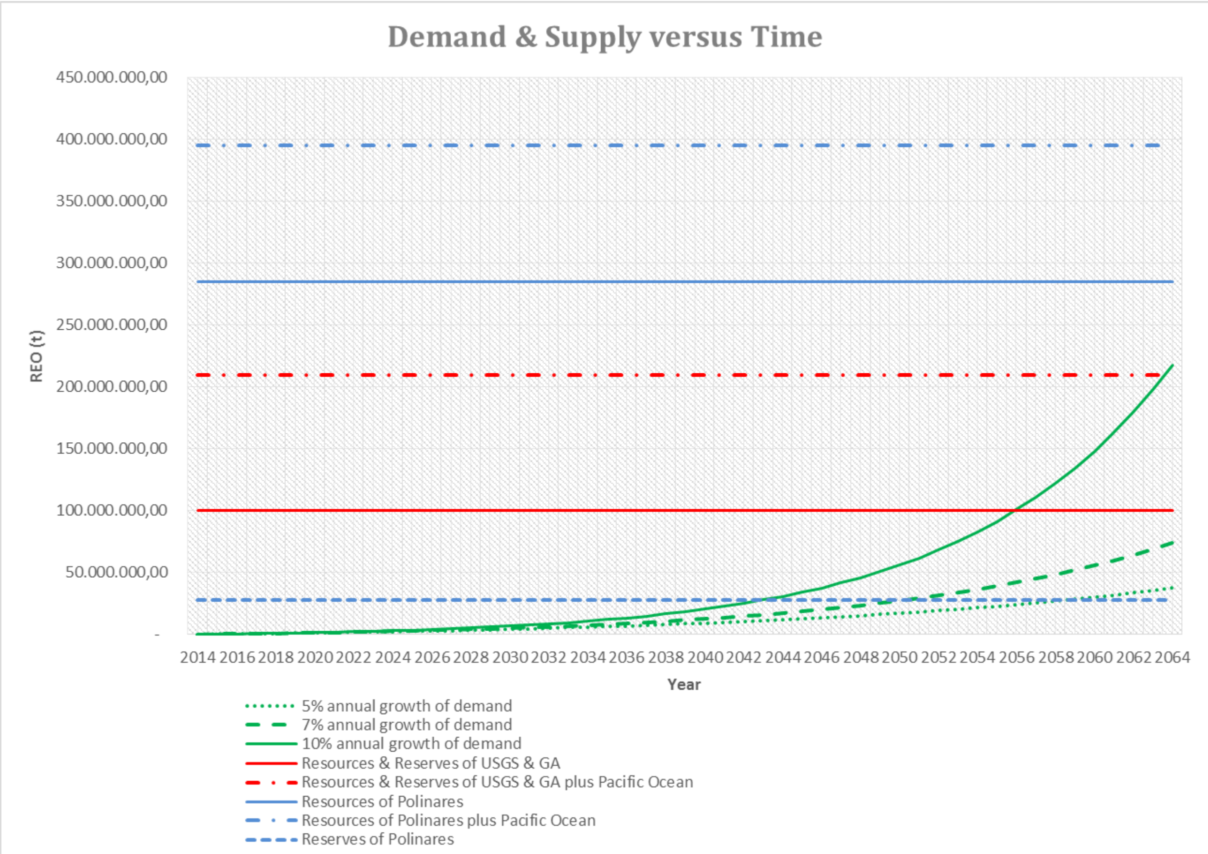


Figure 9: The cumulative demand plotted, together with the resource and reserve estimations for upcoming 50 years.

From Figure 8 follows that for the most pessimistic reserve estimation and for the most optimistic growth of demand, the world is still supplied for the next 30 years with onshore deposits. For the other scenario's, it will take even longer than 40 years. In spite of the one scenario that gives the deep-sea deposits a chance within the next 30 years, it seems it will take longer before it will happen.

But because of the wide range of estimations in Table 3, it can be conclude that there are high uncertainties about the resources in Russia and China. On top of that it can be said that, on history based facts, there is a country risk on Russia and China. With history based facts I mean for example the Ukraine crisis in 2014 and the Rare Earth Crisis in late 00's. So it is imaginable that for example Europe and Japan can't, or don't want to count on the big resources in those countries. Therefore I made an extra figure. The same as Figure 9, but in in this case the figures are corrected. The resource and reserve estimations are subtracted by the values of Russia and China. And the initial demand is subtracted by the share of China.

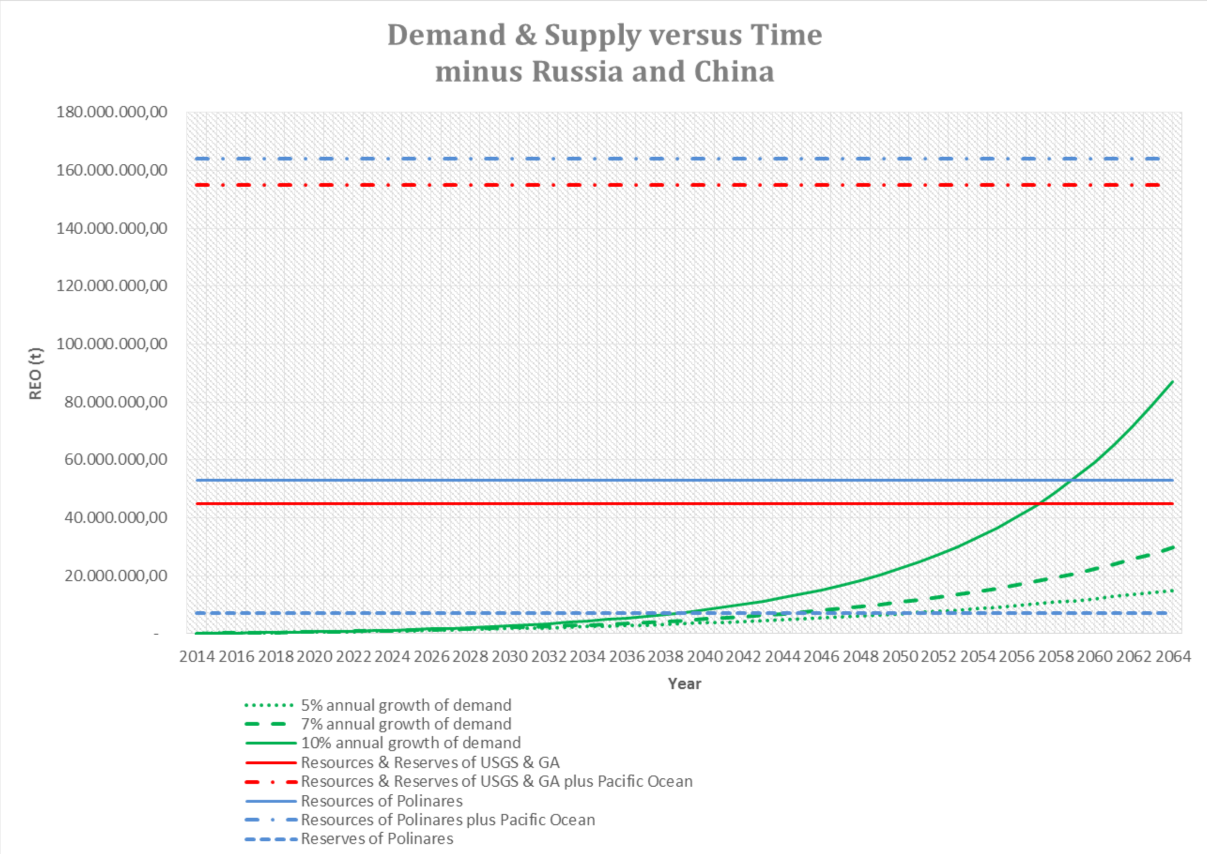


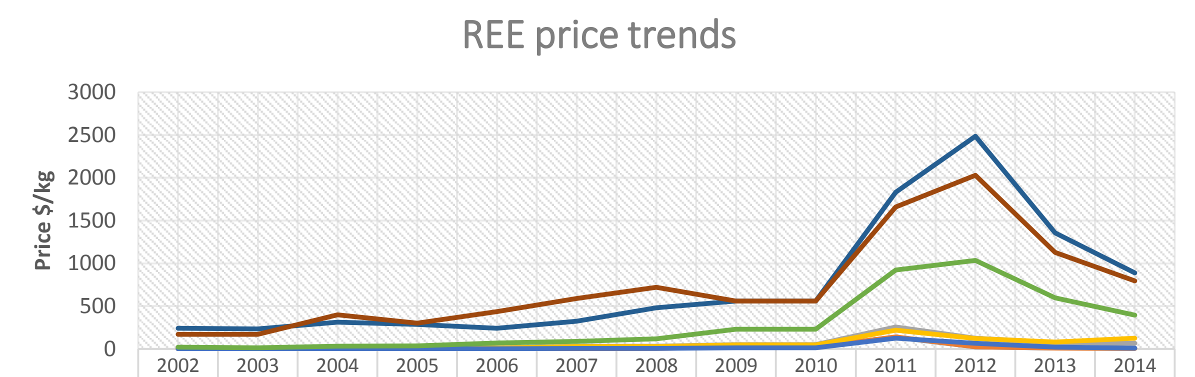
Figure 10: The cumulative demand plotted, together with the resource and reserve estimations for upcoming 50 years and specific for the world, without Russia and China.

From this results Figure 10, which is not that different from Figure 9. And now has to be said that the growth of demand 10% is very unlikely. Two BRIC's nations are ignored, the economic growth and the birth rate in Western nations is low, but on the other side the technological innovation is far higher than the rest of the world. In the 7% expectation plus the most pessimistic reserve estimation, it still will take 30 years, before the onshore supply is dried up.

But maybe we can supply the world for decades with onshore deposits. If it is economically feasible to mine in the deep sea, it still can be worth it.

5. Economic Feasibility

The year 2002 was an iconic year for the Rare Earth industry. For already more than 10 years China was producing REO for low costs. This resulted prices, that low, that the Mountain Pass mine needed to close. After almost a decade of stable prices, China decided to restrict their export. The settled export quota pushed the prices sky-high. After the peak was reached in 2012 the prices dropped, but still the prices didn't fall through the level of before the REE-crisis (Figure 11). These uplift in prices was a reason for companies as Molycorp, Lynas and Arafura to invest (again) in REO-mines. In this chapter I will discuss the cash flow analyses of the mines Mountain Pass, Mount Weld and Nolans Bore, owned by respectively Molycorp, Lynas and Arafura. The mine Mountain Pass will be discussed in detail, as to the other two mines I will stick to the result. At the end of this chapter a cash flow analysis for a deep sea deposit will be discussed.



	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
La	2,3	1,5	1,6	1,5	2,2	3,4	8,7	22,4	22,4	135	25,2	9,71	5,65
Ce	2,3	1,7	1,6	1,4	1,7	3	4,6	21,6	21,6	138,3	24,7	9,92	5,1
Nd	4,4	4,4	5,8	6,1	11,1	30,2	31,9	49,5	49,5	256,2	123,2	72,43	63,5
Pr	3,9	4,2	8	7,6	10,7	29,1	29,5	48	48	220,1	121	81,32	125
Sm	3	2,7	2,7	2,6	2,4	3,6	5,2	14,4	14,4	125,6	64,3	22,18	9
Dy	20	14,6	30,3	36,4	70,4	89,1	118,5	231,6	231,6	921,2	1035	595,72	395
Eu	240	235,4	310,5	286,2	240	323,9	481,9	559,8	559,8	1830	2484,8	1355,36	890
Tb	170	170	398	300	434	590,4	720,8	557,8	557,8	1659	2030,8	1127,15	795

Figure 11: Price trends of several REE during the period 2002-2014. (source: "metal-pages.com")

Prices

The mentioned prices are all '99% oxide min FOB China' in $/kg (FOB: Free on board). This means it is the price someone needs to pay for 1 kg, 99% pure, Rare Earth Oxide on the borders of China. All the costs between the mine and the border are paid by the seller. The reason I chose for these prices is that almost all REO-prices are China-based and the FOB-prices are the prices that a non-Chinese company needs to compete. The used prices are given in Table 6.

The occurrence of REE in the Deep Sea is given in ppm REE, and not in tonnage REO. Therefore in the calculations for the Deep Sea cash flow I used the '99% metal min FOB China' prices. The prices are given in the second column Table 6.

Element	99% oxide FOB China		99% metal FOB China	
Scandium	$	*5,50*	$	*13,00*
Yttrium	$	15,00	$	60,00
Lanthanium	$	5,65	$	10,50
Cerium	$	5,10	$	13,00
Praseodymium	$	125,00	$	155,00
Neodymium	$	63,50	$	85,00
Samarium	$	9,00	$	29,50
Europium	$	890,00	$	1.250,00
Gadolinium	$	46,50	$	132,50
Terbium	$	795,00	$	920,00
Dysprosium	$	395,00	$	625,00
Holmium*	$	380,00		
Erbium*	$	72,00		
Ytterbium*	$	1.450,54		
Lutetium*	$	2.261,58		

Table 6: REE-prices on June 10th 2014. ('metal-pages'). *For Holmium, Erbium, Ytterbium and Lutetium different sources are used. ('mineral prices' and 'ali express')

Cash Flow Analysis

To calculate the cash flow the following equations are used.

$$F_k = N_k - O_k - C_k - r_R N_k - T_R I_{BT-k}$$

And

$$I_{BT-k} = \left((1 - r_R)N_k\right) - O_k - \left(\frac{C_1}{D_1}\right) - \left(\frac{C_2}{D_2}\right)$$

Definitions:

F_k = Cash flow in year k
N_k = Revenue in year k
O_k = Operational costs in year k
C_k = Capital costs in year k
r_R = Royalty rate
T_R = Tax rate
I_{BT-k} = Income before tax in year k
$C_{1,2}$ = First or second investment for the first or second phase in the project
$D_{1,2}$ = Time reserved in years for depreciation of the first or second investment

The present value in year k is:

$$PV(k) = \frac{F_k}{(1 + r_d)^k}$$

Extra definition:

r_d = Discount rate

The net present value (NPV) is the cumulative present value over k years.
If the discount rate is equal to the Internal Rate of Return (IRR), then the NPV will be 0 at the end of the project.

Transportation Cost

Comparing to more common metals, the REO-market is relatively small. To estimate the shipping costs of REO it is inevitable to make an assumption, which is based on a different metal. The shipping costs for iron ore are approximately 22$/ton (Kirschenblat, 2014). This is the same as 0,02$/kg. If we copy this to the REO, it would be negligible, because of the high resource prices of REO (range 10-1000$/kg). Of course it has to be said that iron and REO are two different resources and the transport volumes of iron ore are much higher.

Mountain Pass (California USA) – Molycorp

In 2011 Molycorp restarted the Mountain Pass mine. In 2014 they reached full production with 19.050 tonnage of REO each year. If the future is promising Molycorp can boost their production up to 40.000 tonnage, but in 2013 these activities where delayed for an indefinite time. The mined ore contains several elements in form of oxides (REO). This distribution is shown in Figure 12. These numbers, and the prices from Table 6 are combined in Table 7 to calculate the revenues.

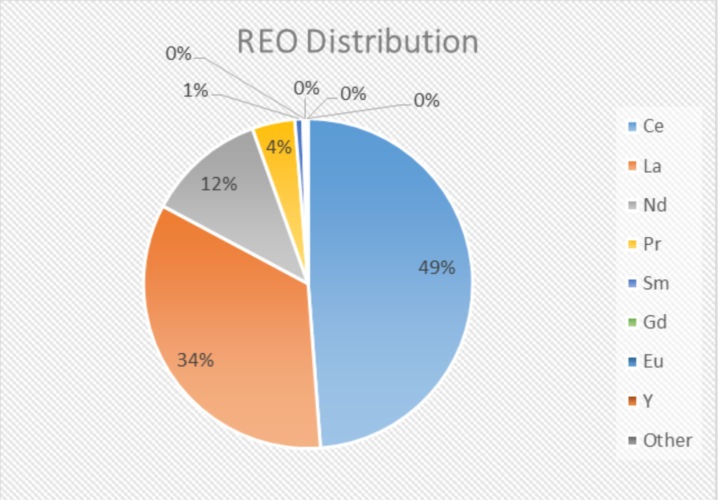


Figure 12: The distribution of several elements in the mined ore.

REVENUES				
Annual production (t)	19050			
	Element	Fraction	Mass	Revenue
		(-)	(kg)	(99% Oxide FOB China)
REO distribution	Ce	0,488	9296400	$ 47.411.640,00
(Molycorp report 2012)	La	0,34	6477000	$ 36.595.050,00
	Nd	0,117	2228850	$ 141.531.975,00
	Pr	0,042	800100	$ 100.012.500,00
	Sm	0,0079	150495	$ 1.354.455,00
	Gd	0,0021	40005	$ 1.860.232,50
	Eu	0,0013	24765	$ 22.040.850,00
	Y	0,0012	22860	$ 342.900,00
	Other	0,0005	9525	
			Total:	**$ 351.149.602,50**

Table 7: Calculations of the revenues.

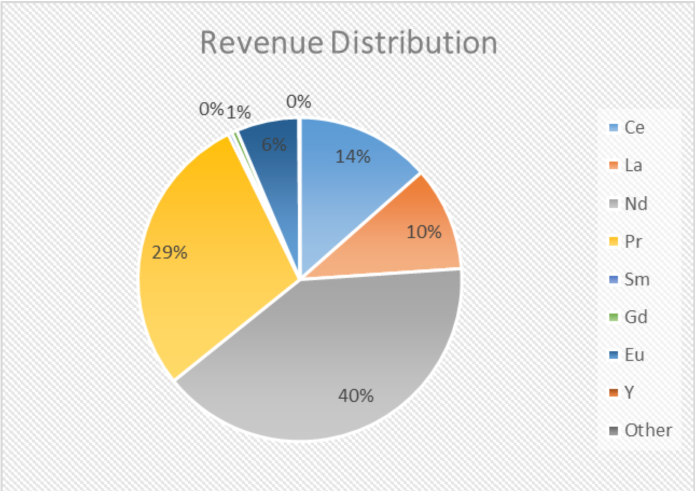


Figure 13: The stake of each element in the revenues.

Figure 13 illustrates the correlation between each of the elements and the revenues. For example Praseodymium and Europium, these have a low occurrence, but take a huge part in the revenues.

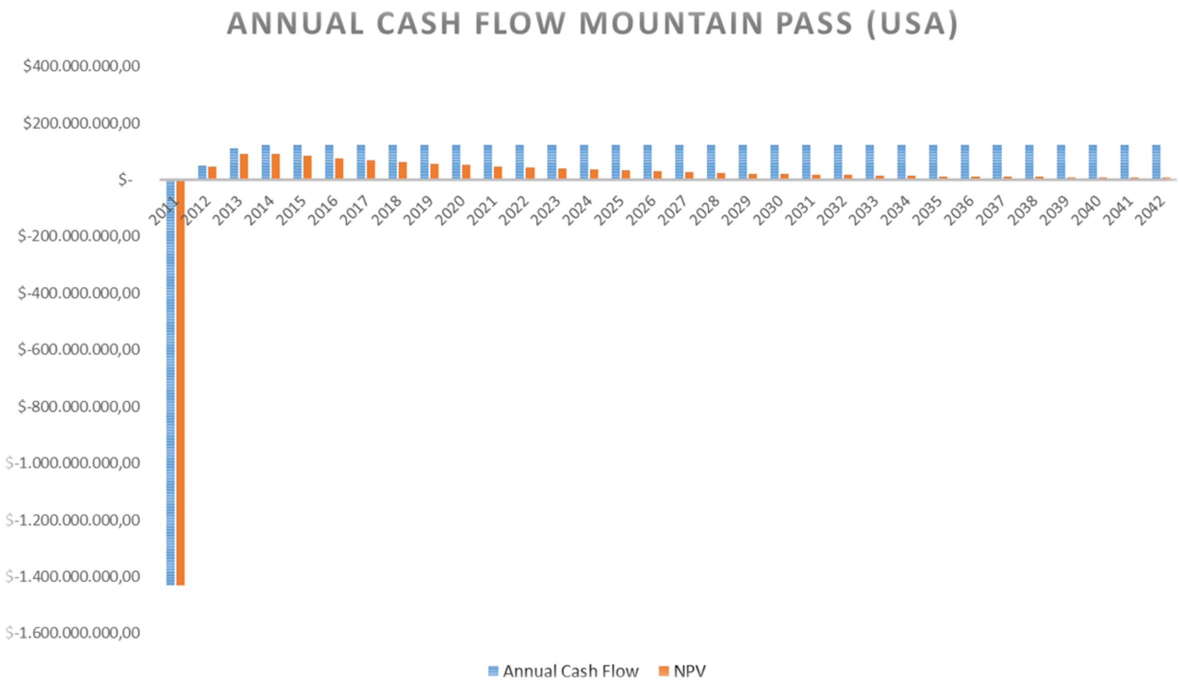
The restart costs of the Mountain Pass mine are according to Molycorp $1.000.000.000. Thereby Molycorp has invested in a separation plant of $450.000.000. The total capital costs are therefore $1.450.000.000. Molycorp doesn't mention a depreciation time for the investment. Therefore I made the assumption that the investment would be depreciated over lifetime and that would be 31 years, because Molycorp has a mining permit till 2042.

In 2011 Fortune magazine published that the operational costs of the Mountain Pass mine are only 2,76 $/kg. The reason for such a low costs is the efficient way to retreat waste from the process. The total annual operation costs are $52.578.000.


Figure 14: View on the Mountain Pass mine in California. (source: smartplanet.com)

Furthermore it is assumed that Molycorp needs to pay federal and state taxes. According to PWC (Price Waterhouse Coopers) the royalty rate is 30% and the federal tax rate is 35%. And according to the California Franchise Tax Board the federal tax rate is 8,84%.

By using all this information, a cash flow can be created. (Figure 15)



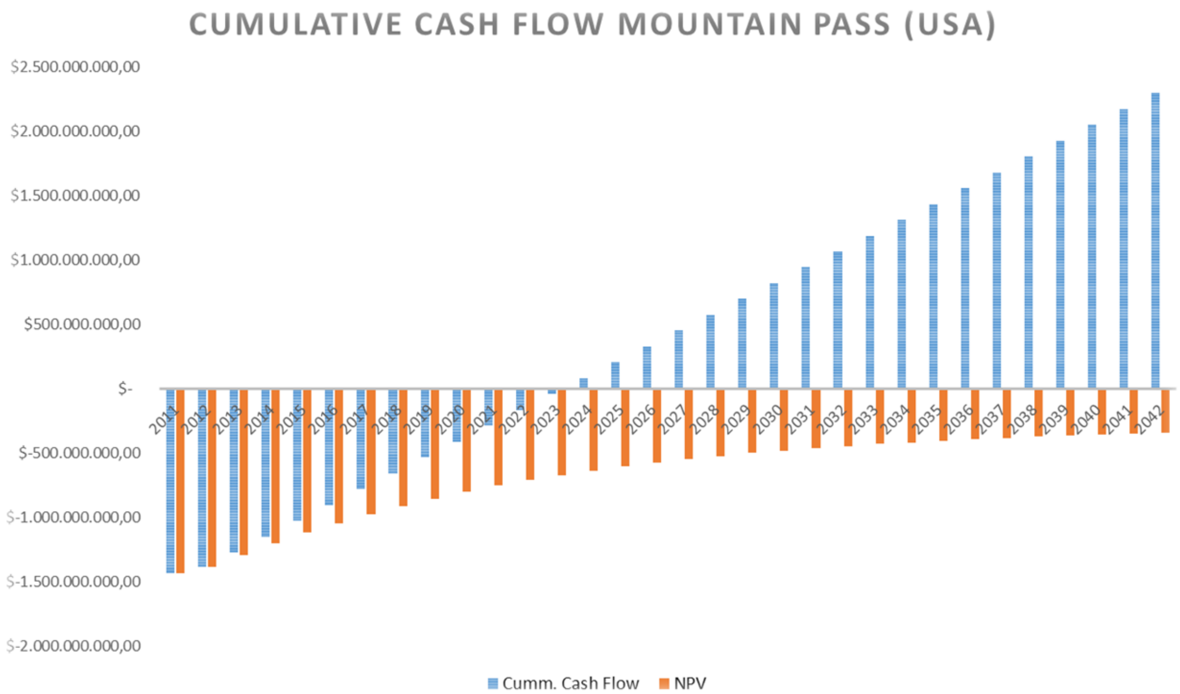
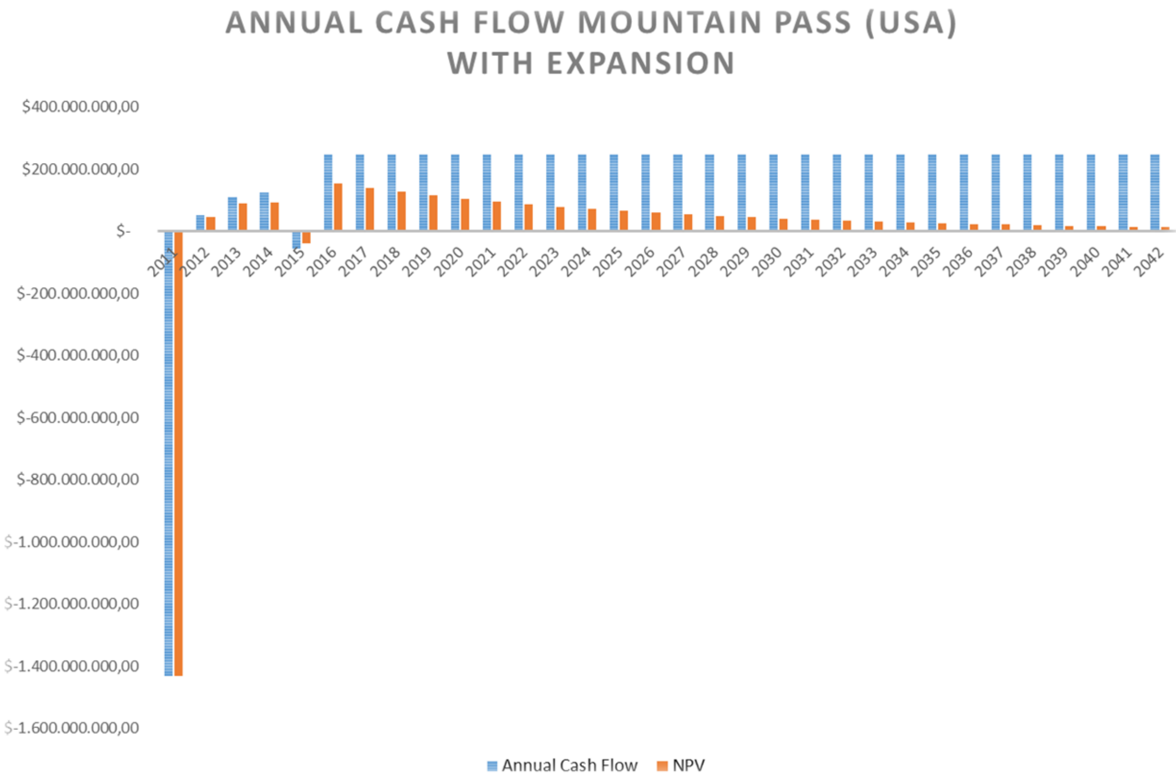


Figure 15: The annual and cumulative cash flow of Mountain Pass. For the NPV a discount rate of 10% is used.

As can be noticed in Figure 15 Molycorp takes risks by restarting the Mountain Pass mine. For a discount rate of more than 7% (Internal Rate of Return – IRR), the NPV will be below zero. It is possible that Molycorp believes that the discount rate will be lower than 7%, because of a possible continuation of an era with higher REO-prices. Thereby Molycorp has the opportunity to expand their mine and double their production. Let's say Molycorp decides to expand in 2015. The IRR will increase to 12% and the cash flow will look like this. (Figure 16)



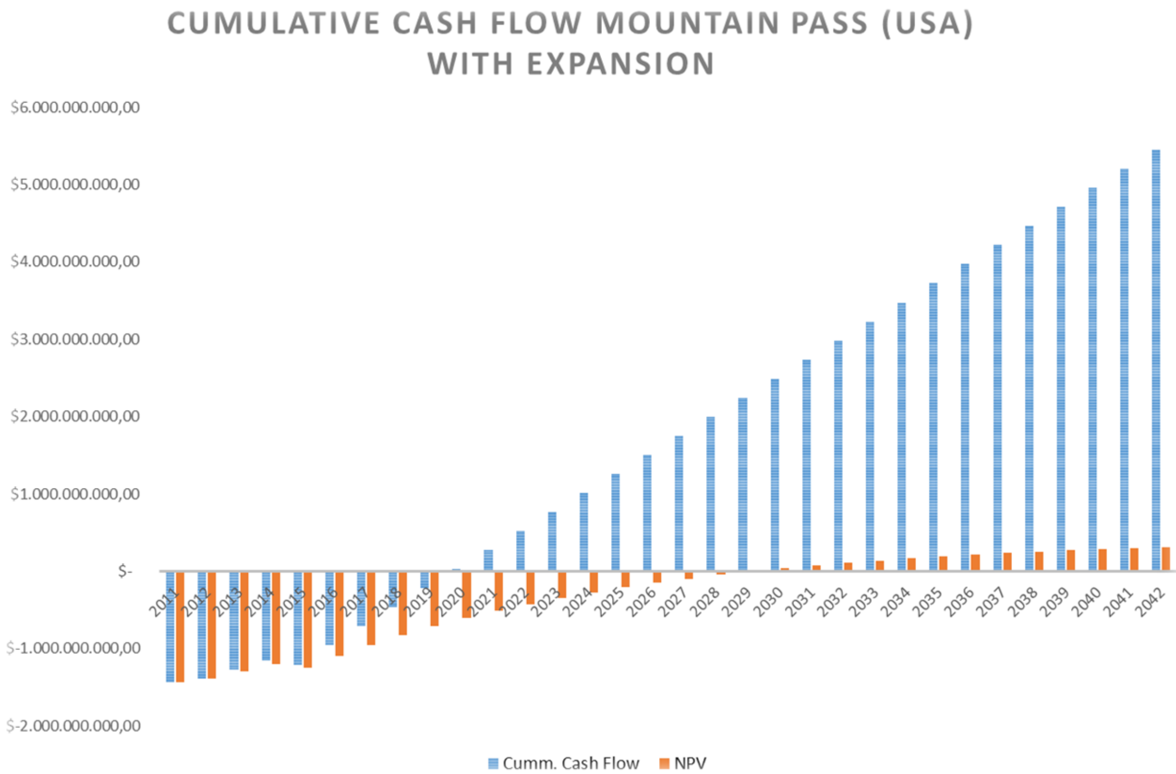


Figure 16: The annual and cumulative cash flow of Mountain Pass including a possible expansion in 2015. For the NPV are discount rate is used of 10%.

As can be noticed the mine could be economically feasible in the current circumstances. But for the future the discount rate needs to be low, or Molycorp needs to expand the mine to take a stand for unsuspected circumstances. However Molycorp believes the deposit is economically feasible and started to produce again in 2011 and delayed the expansion for an indefinite time.

Situation 2002

*To illustrate the situation in 2002, I used the prices in 2002 (*Figure 11*). The revenues of Mountain Pass would have been roughly $58 million. Put this against the operational costs of at least $52 million there is not much left to pay off the investments. Thereby it is possible that the operational and capital costs were much higher in 2002 than nowadays.*

Mount Weld (Western Australia) – Lynas Corporation

Mount Weld is located in Western Australia and exists out of two deposits. The Central Lanthanide Deposit (CLD) and the Duncan deposit. Both deposit have a different distribution of elements. Lynas Corporation started to mine the CLD in 2011 and reached full capacity (22.000 t) in 2013. The Duncan deposit seems to be economically feasible, but it is unknown when Lynas starts to mine the Duncan deposit. When they do, they will mine annual 13.000 t. Taking these numbers in to account, the revenues can be calculated analogous with Table 7 and this results in $651.000.000 for CLD and $529.000.000 for the Duncan deposit. The reason for this huge difference between each other and the Mountain Pass mine is the enrichment of more different and more worthy elements. (Figure 17 & Figure 18)

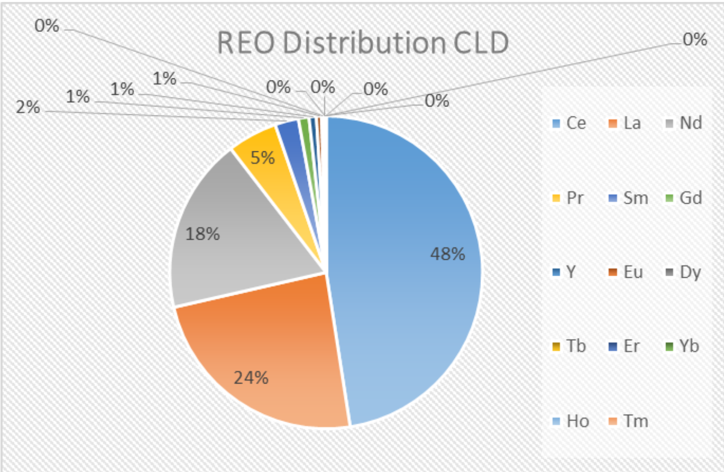


Figure 17: Distribution of the elements in the Central Lanthanide Deposit.

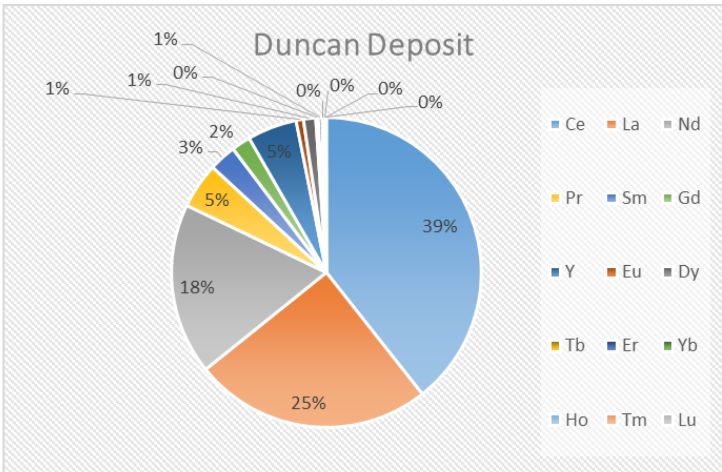


Figure 18: Distribution of the elements in the Duncan Deposit.

The starting costs for Lynas Corporation were relative low, only $300.000.000. But to start the Duncan Deposit, it takes more, due to the special chemical treatment of the mined ore. This project will cost $600.000.000. In regard of operational cost Mount Weld is less favoured. The ore refinement process is very complex because of the presence of radioactive elements as Thorium and Uranium. After mining, the ore is transported to Malaysia where it is refined. Because of this, the operational costs are 10,12 $/kg (Fortune, 2011). In total $223.000.000 for CLD and $132.000.000 for the Duncan deposit.

A few last details. According to PWC the federal tax rate is 30% and the royalty rate is 30%. The life expectancy is according to Lynas more than 20 years.

These numbers result in a cash flow with a high certainty on a positive income. For a discount rate of 10% the cumulative revenues for the mine without the Duncan deposit is $1,06 billion and with the Duncan deposit it is $1.7 billion. The internal rate of return is 41-43% for both scenarios. Cash flow graphs like Figure 15 & Figure 16 can be found in Appendix B.

Nolans Bore (Northern Territory – Australia) – Arafura Resources

North of Alice Springs in Australia lies the mine Nolans Bore. Arafura Resources has started to operate in 2013, went in full production in 2014 and wants to go on till 2035. Annual 20.000 tonnage of REO is mined. The high percentages of Neodymium and Europium take the revenues up to $605 million. The investments Arafura had to make for the mine and the separation plant were $657 million. The operational costs are $376 million annually. This is extremely high. Converted to $/kg, it means that Arafura Resources pays 18,80 $/kg. But Arafura doesn't mention taxes and royalties in the Financial Plan of 2010. A possibility is that the royalties and taxes are included into the operational costs. (Arafura, 2010)

With these numbers Nolans Bore has a high profitability chance. The internal rate of return is 21% and for a discount rate of 10% the cumulative revenues will be $512 million in 2035. Cash flow graphs like Figure 15 & Figure 16 can be found in Appendix B.

South East Pacific Ocean

In 2011 the Nature Science published an article about Rare Earth deposits on the deep sea of the Pacific Ocean. It gave a very detailed view about the REE on a few locations. It claims there are potentially over 110 million tonnages of REO spread out over the Pacific seafloor. This raises the question: is it economically feasible to mine it? To answer this question we need to calculate all factors.

Let's start with al technical possibilities. At this moment there is one company on the break through to start mining 1600 m below sea-level near the coast of Papua New Guinean (Solwara Project). This company is Nautilus Minerals Inc.. However Nautilus doesn't mine REO, but copper and gold, but I assumed their technique is versatile and could be used also for the mining of REO.

In 2010 SRK Consulting made a cost study for Nautilus. In this study someone can find besides financial, also production figures. SRK believes Nautilus can mine 3.500 tonnages of raw ore each day, or 1,28 Mt annually. The investments that are required to make this operation possible are estimated by SRK on $381 million, but a separation plant is excluded from this number. Based on the other discussed mines, the costs for a separation plant are between the $200 and $500 million. For this situation I assumed it would be a small, normal and less high tech plant, because the investments are already high, and therefore I used $300 million as capital costs for a separation plant. The capital costs are in total $681 million.

Furthermore SRK reports operational costs of 70$ per tonne, whereby a contingency is included of 17%. The total operational costs is therefore annual $95 million. To complete the financial figures: Nautilus reports it is paying 32,25% of royalties. Taxes are not mentioned, therefore I assumed 30%, just like the other discussed mines.

Now we know the costs and the production of raw ore, we want to calculate the income. For the revenues, I used the article "*Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements"* by Kato et al. published by Nature Science.

Kato is focussing on specific two areas in the Pacific Ocean, the Central North part and the South East part. The last one is the most enriched part and this part I used in my calculations. According to Kato the content of the mud on the seafloor is comparable with the Chinese deposits, but except for the heavy rare earth elements, their abundance is twice as high as those in China. The distribution is, thanks to Arafura Resources, known and I adapted those figures with the knowledge from Kato. (Figure 19) The average amount of REE in the mud is 1.180 ppm. Combine this figure with the production, it means that of the 3.500 tonnage ore that is mined daily, 0.12% is a REE. In other words annually 1.533 ton of REE.

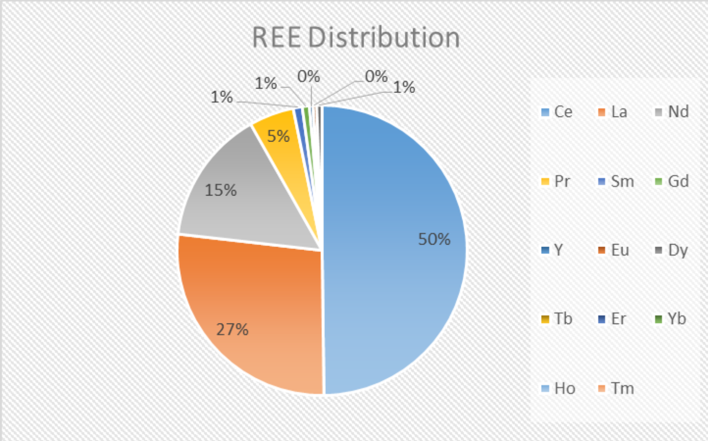


Figure 19: Distribution of the elements in the South East of the Pacific Ocean.

In reality the rare earths will oxidize and will not be sold as metals, but I still chose to continuing calculating with the 99% metal prices. The reason for this is that the REE distribution is known and is different from the REO distribution. This is because every element is oxidizing with a different amount of oxygen and therefore the mass change is different.

According to this information the revenues are annually $62 million. That is far distanced from the production costs of $91 million. And in spite of the huge gap, it is possible that the production costs are much higher. Nautilus wants to mine at 1600 meters below sea level, the rare earth deposits in the South East Pacific lie at 4000-5000 meters depth. And where the deposits of Nautilus are located just before the coast of Papua New Guiney, the deposits in the Pacific are at thousands of kilometres distance from the mainland. And to complete these remarks, in the operational costs, given by Nautilus, refinement costs are excluded.

Situation 2011-2012

During the peak in 2011-2012, the REE prices went sky-high. With these prices, the calculation results in a much different revenue. With the prices of 2012, the revenues would go up to beyond the $90 million, enough to pay the operational cost. And 2011 beats 2012 with revenues far beyond the $250 million. However it is very unlikely to get a long-term stable market with the prices of 2011. This because of the possibility of several technical solutions like recycling or substitution.

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6. Alternative Solutions for Shortages

Recycling

In 2011 only 1% of the REE demand, was supplied through recycling. (Binnemans et al., 2013) In Europe there is only one company; Rhodia in France, that is specialised in the separation of heavy rare earth elements and that only since 2012! Besides that there are a few companies active in the recycling of light rare earth elements. (Korteweg et al., 2012) These facts illustrate that the recycling of REE is still in its infancy. There are several reasons for this infancy. The first and most important one is that recycling isn't economically feasible for many of the REE. In the early 90's the recycling of SmCo magnets was economically justified, but nowadays these elements are less important and critical in comparison with Nd in NdFeB magnets. And the moment that these elements are passing a not defined critical point, the recycling will get a financial boost of investments to overcome the other barriers into recycling. The so called barriers are for example inefficient gathering of scrap, small concentrations of REE in scrap, labour-intensive and technical complexity of the process. (Binnemans et al., 2013), (Korteweg et al., 2012)

The mentioned critical point is depending on several factors. Of course the resource prices are important. The prices need to be high enough, before the REE extraction will (partly) switch from mining to recycling. But it wouldn't involve the REE, if it was that easy. As it happens the prices between the REE separately are not uncorrelated. That means that to fullfil the demand of, for example, neodymium, and because these elements are rarely separated, there forms a surplus for other elements. This is followed by a price drop and the share of the elements in the revenues drops. For mining companies it is therefore attractive to invest in recycling for exclusively neodymium to keep all the prices on a stable (high) level. This means that recycling of neodymium is more profitable than increasing the mining activities. An example of a company that is working conform this strategy is Molycorp. (Binnemans et al., 2013) On top of that, it is a solution of the neodymium shortages.

Innovation

As mentioned before Japan has a high demand for REE, but does not own rare earth deposits. The result of this is the research for deep-sea deposits, but Japan is also investing in innovation of REE involved products. In the field of magnets, catalysts and others, respectively 65%, 37% and 33% of the patents come from Japan. The rest of the patents comes mostly out of Europe and North America. The role of China is fractional. (Kortweg et al. 2012)

These developments into the innovation are causing a smaller dependency on risky countries and leading to a more stable market.

Substitution

Despite the substitution of REE is theoretical possible, real examples are absent. (Kortweg et Al. 2012) Because of the price developments the research towards substitutions is growing. Like I just said in the chapter 'innovation', countries with a low supply certainty are investing in innovation. And substitutions is one of the possible subjects to be investigated.

To conclude, it seems that the alternative solutions for potential shortages are still in its infancy and research is ongoing. These developments could delay the moment that deep-sea mining could become profitable.

7. Future Obstacles for Deep-Sea Mining

Public Debate

Hydrothermal vents are called the oases of the deep oceans. The vents are providing the spots with a lot of thermal energy, which makes life in those extreme conditions possible. Whereby the temperature normally drops to 2ºC, the temperature around those vents is sometimes heated up to over 400ºC. Because of the absence of light, the present micro life needs a different fuel energy and finds it in the chemical reactions that are taking place around the vents. The unique properties, their capabilities, and their ecological importance are still unclear. (Fisher et Al. 2007). Therefore it is causing a public debate. Nature conservation organizations are anxious because of the lack of knowledge about the ecology in the deep-sea.

It is important to know what the consequences of deep-sea mining are. But on the contrary it is the drive to a sustainable society, what makes the deep-sea so interesting. The REE and other precious metals are continuing linked with sustainable products and as long as this drive is growing, the interests for deep-sea mining will grow with it.

That the society strives for more sustainability is because of several factors, mostly a few disasters. The most important one is the greenhouse effect and the most recent one is the Fukushima nuclear disaster. These factors are creating a growing desire for green and a non-nuclear energy and let it be that REE are playing a crucial role in it. Take windmills and solar panels as example. To provide windmills with a maximum life time, it is essential to use NdFeB magnets and for solar panels are Terbium and Erbium are crucial.

It is important that the public debate is open minded and well substantiated. Sustainability can lead to deep-sea mining, but if we block deep-sea mining, it could lead to a less sustainable society. Therefore it is essential to know what the consequences of both ways are.

The United Nations Convention of the Law on the Sea

"The treaty of 1982, that went into effect in 1994, had as main purpose to create international waters. These international waters and its mineral resources, according to the Treaty, belong to the common inheritance of humanity and no state may claim the authority or the sovereign rights over any part of the area and its mineral resources. These mineral resources one should think mainly of gas hydrates, hydrothermal ore deposits and manganese nodules." (Taverne, 2012)

Nowadays this Treaty, the United Nations Conventions on the Law of the Sea, is ratified by 166 nations. It illustrates the importance of this law which defines the borders on the sea. One of the most important borders that has been defined by this Treaty is the Exclusive Economic Zone (EEZ). Within this area the government has sole rights for exploitation of the present natural resources. The EEZ extends out to maximum 200 nautical miles (or 370 km) from the baseline (low-water line). Figure 20 shows the international waters and the EEZ's.

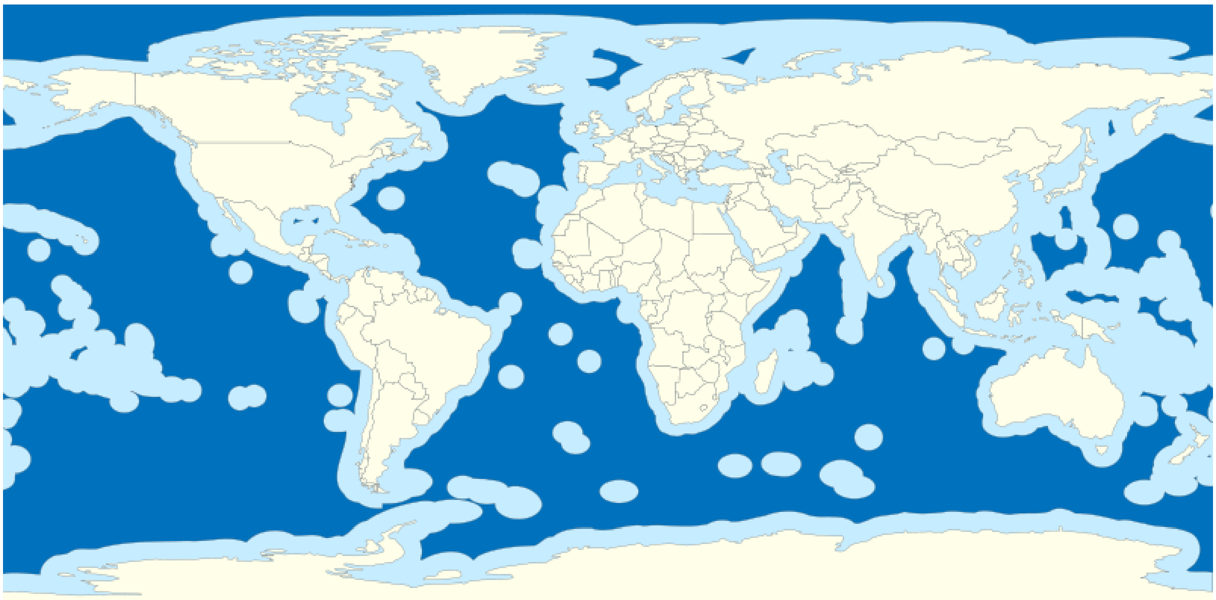
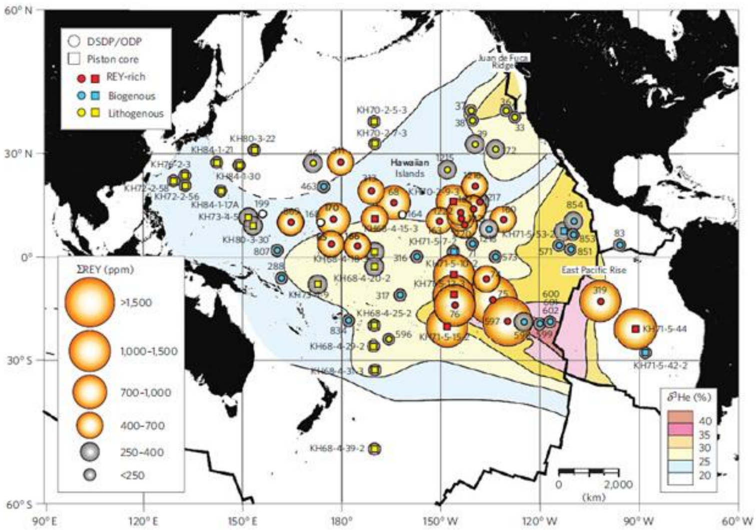


Figure 20: A map of the international waters (dark-blue) and the Exclusive Economic Zones (light-blue).

It is obvious that with this in mind, the potential of deep-sea deposits could make a downfall. Although the exploitable zones are still huge, one can see in Figure 21 that many areas with high potential, are located in international waters. This means that the estimate of 110 million tons of REO needs to adjusted to a lower value. But this has less consequences for companies who would invest in deep-sea mining. If the prices would raise that high, and deep-sea mining becomes economically feasible, there could be still enough deposits located inside the EEZ of nations.

Figure 21: Distribution of average REY contents for surface sediments (<2min depth) in the Pacific Ocean. (Kato, 2011)



8. Conclusion

The rare earth crisis, caused by China in the late 00's, was a wake-up call for the world. After decades of low resource prices during the so called Chinese era (Figure 7) the gold rush for the elements and the research for innovations had started off. In the first year the prices raise sky-high, but the reaction of the world was fast and effective. The (re)opening of a few old and new mines stabilized the prices more or less on a lower level than 2011, but still on a much higher level than before the crisis. And as discussed there are still many economically feasible deposits, ready to start mining. Eventually, these developments could lower the price further.

The search for new deposits that are (potentially) economically feasible delivered fast and positive results. This includes the rare earth deposits in the deep-sea environment. But the estimated onshore supply seems to be capable to answer to even the positive expectations of the growth in demand. It would take (much) longer than 30 years before the onshore supply will be exhausted. And also for countries with no resources, but a high demand, the future is less negative than expected. When the Chinese market is closed, nations as Japan and Europe can still rely on resources in North America and Australia, for (more) than 30 years.

As for the economic feasibility of deep-sea mining, there is still a long way to go. For companies who want to invest in deep-sea mining, the REO-prices need to stabilize on a 2011-level to become capable to manage the extreme high operational costs of deep-sea mining. However there is a small potential, when the mining of REO is combined with the mining of other valuable metals it could be profitable. But purely for the REO it is economically not feasible.

For the long term future, or in the case of a pessimistic scenario, there could be a small chance that the interests to mine rare earth deposits in the deep-sea environment would become reasonable. But it seems more likely that this critical moment will be delayed because of powerful innovations into the substitutions and the recycling industry. On top of that a negative public debate or the United Nations Convention on the Law of the Sea could square the potential of the deposits up.

To conclude, the potential of rare earth deposits in the deep-sea environment seems extremely low for at least the upcoming decades.

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Appendix A

Country	Location	Production [t/a]
Australia	Mount Weld	22.000
Australia	Nolans Bore	20.000
Brazil	Morro Dos Seis Lagos	2.105
India	Chavara	2.700
India	Wako Bussan Co	1.090
Malaysia	Ipoh	450
Russia	Lovozero	3.000
USA	Mountain Pass*	19.000
Vietnam	Dong Pao	4.000
China	Total	95.000**
Total	-	**169.345**

Table A 1: Current operating REO-mines or mines that will open in 2014. *Mountain Pass can increase their production up to 40.000 t/a when the market asks for it.The production in China has dropped to 95.000 t/a since 2009.**

Country	Location	Production [t/a]
Canada	Hoidas Lake	4.000
Greenland	Kvanefjeld	43.700
Kazakhstan	Ulba Tailings	15.000
South Africa	Steenkampskraal	2.500
Other mines (2014)	-	169.345
Total	-	**234.545**

Table A 2: REO-mines that will open in 2015

Country	Location	Production [t/a]
Australia	Dubbo/Toongi	4.800
Canada	Strange Lake	13.000
Canada	Nechalacho	10.000
USA	Bear Lodge	10.000
Other mines (2014&2015)	-	234.545
Total	-	**272.345**

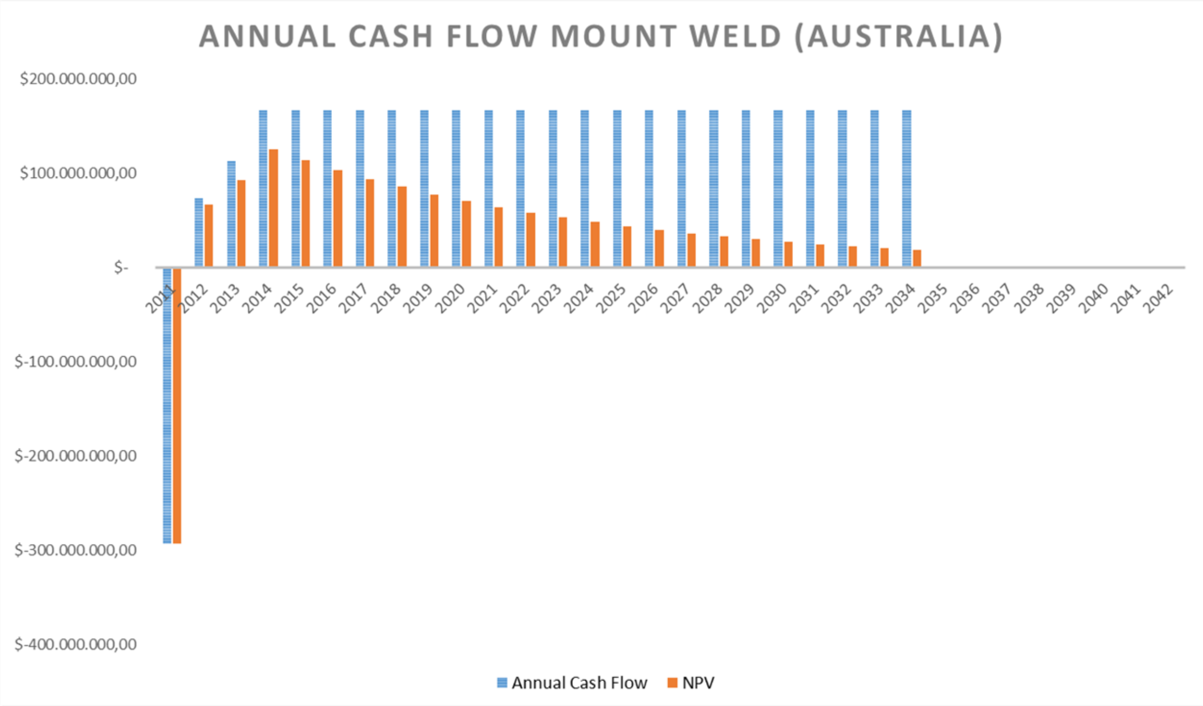
Table A 3: REO-mines that will open in 2016 or 2017.

Country	Location
Argentina	Rodea de Los Molles
Australia	Mary Kathleen
Australia	Olympic Dam
Australia	WIM 250
Brazil	Pintinga
Canada	East Kemptville
Canada	Kipawa
Canada	Misery Lake
Canada	Zeus
Canada	Eco Ridge
Finland	Korsnäs
Kyrgyzstan	Kutessay II (HREO)
Madagascar	Tantalus
Namibia	Lofdal

South Africa	Zandkopsdrift
Sweden	Norra Karr
Tanzania	Wigu Hill
USA	Bokan Mountain
USA	Spor Mountain
USA	Lemhi Pass
Vietnam	Yen Phu
Vietnam	Mau Xe North and South

Table A 4: Deposits that are economically feasible and some of the deposits will be mined shortly after 2017.

Appendix B



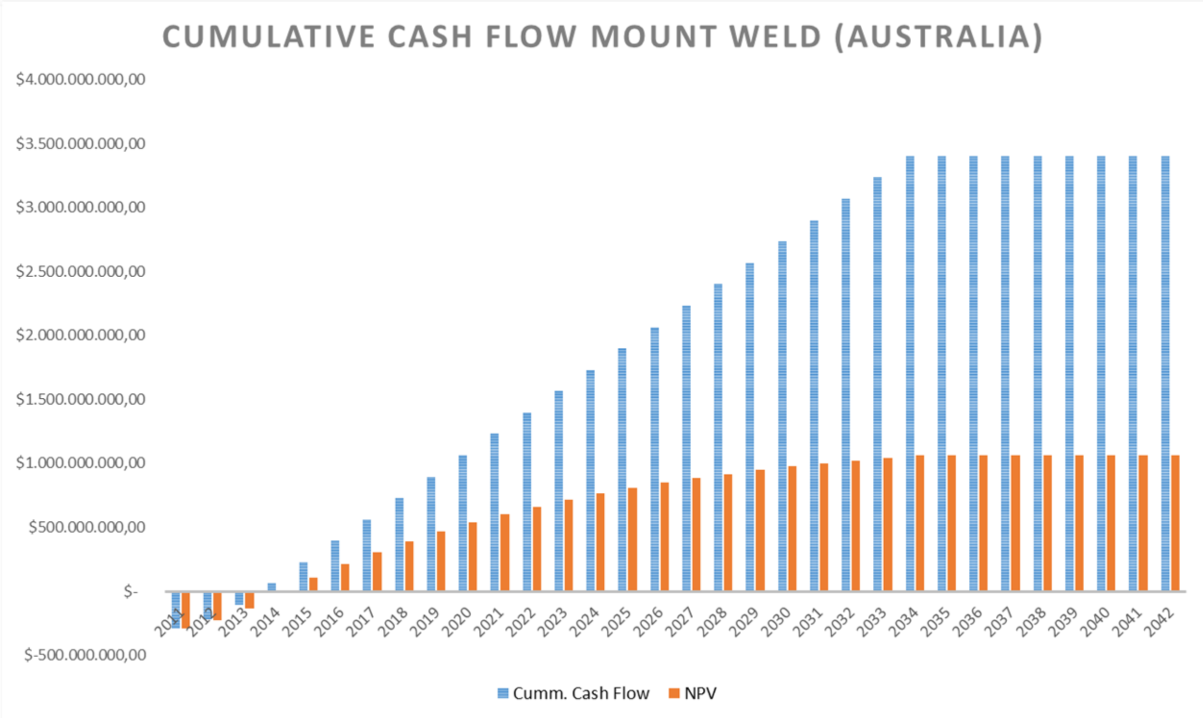
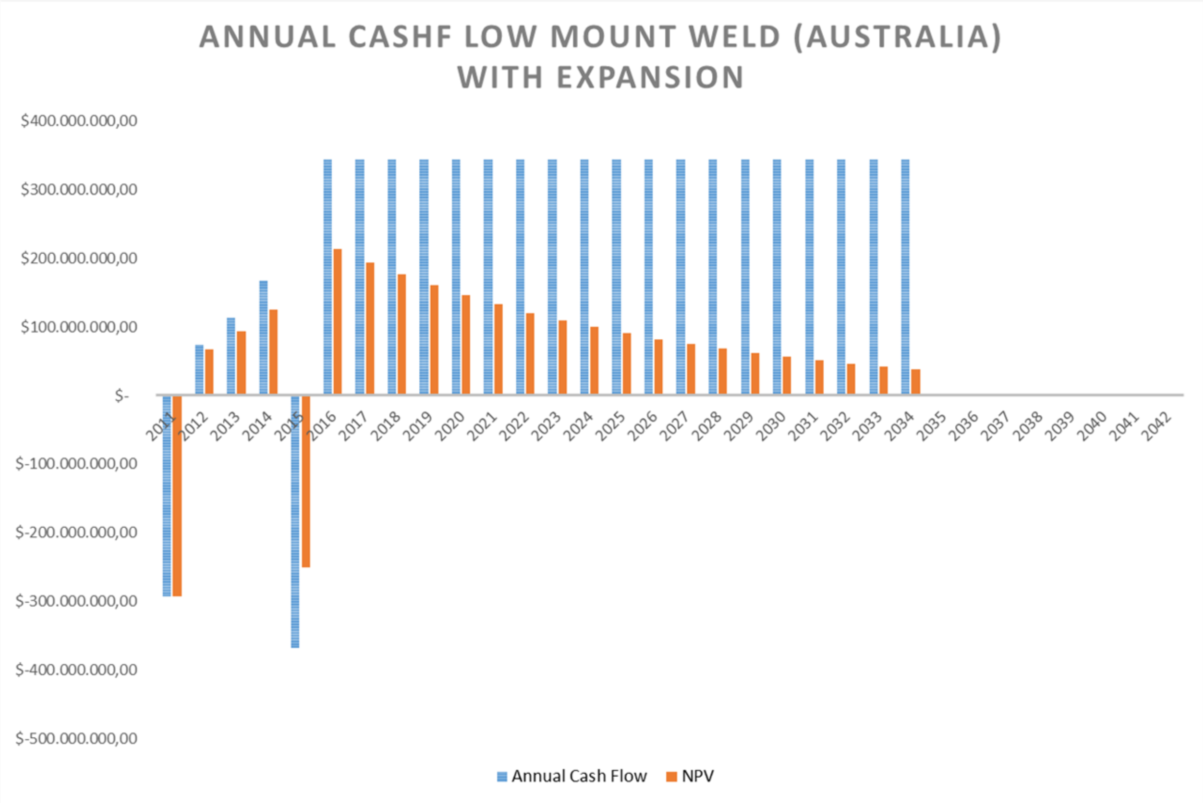


Figure B 1: The annual and cumulative cash flow of Mount Weld. For the NPV a discount rate of 10% is used.



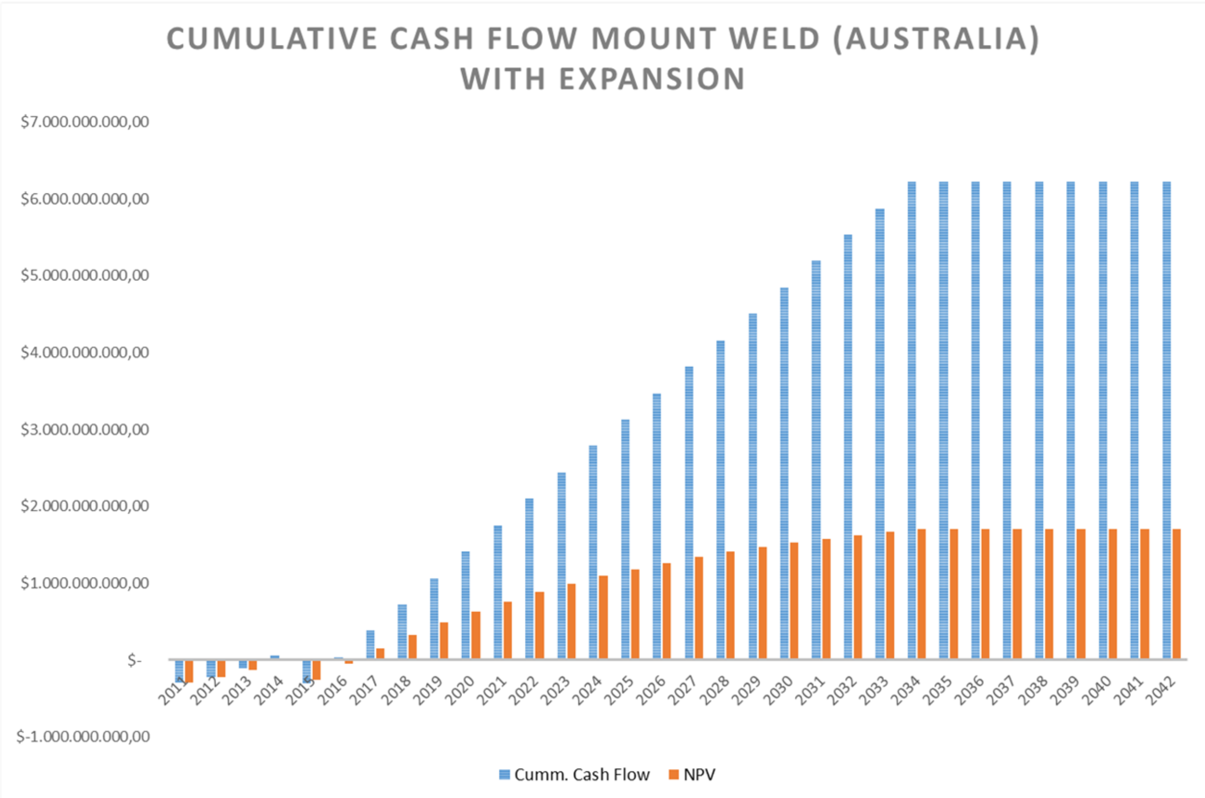
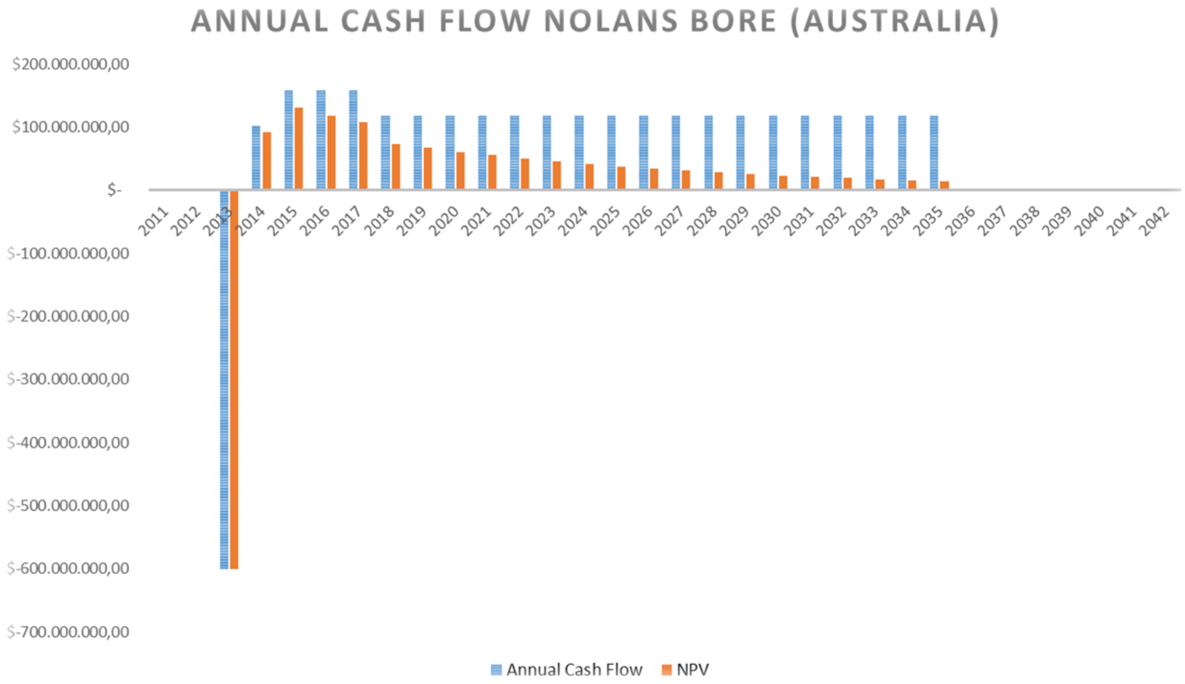
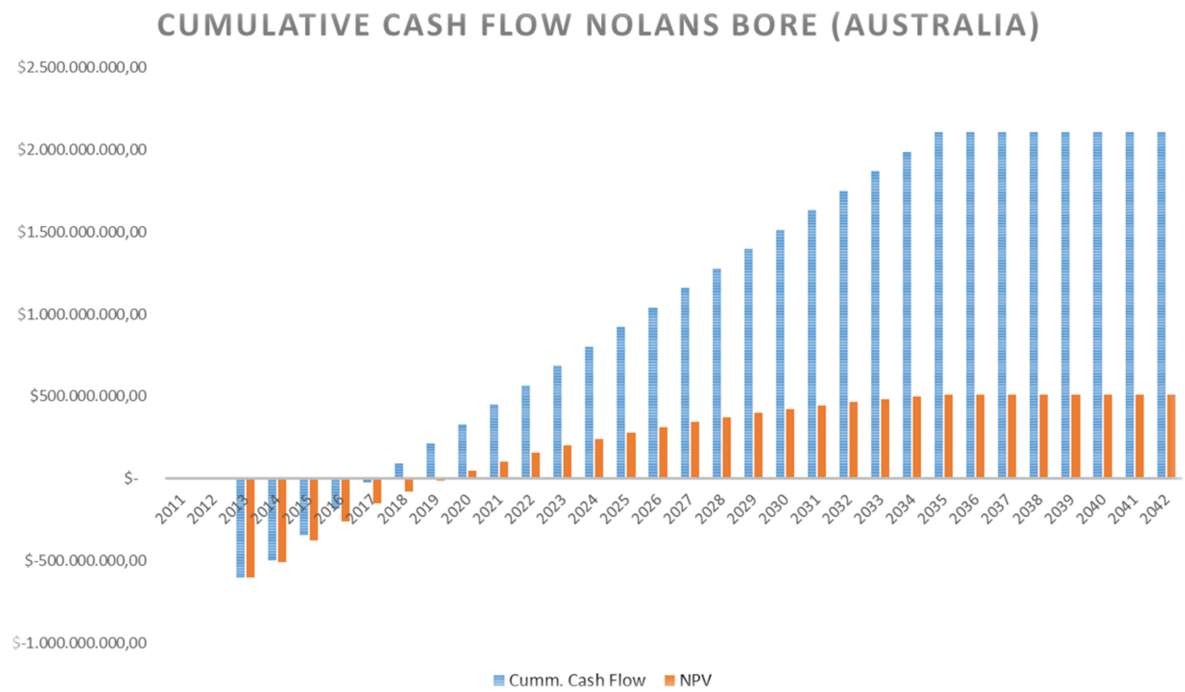


Figure B 2:The annual and cumulative cash flow of Mount Weld including a possible expansion in 2015. For the NPV are discount rate is used of 10%.





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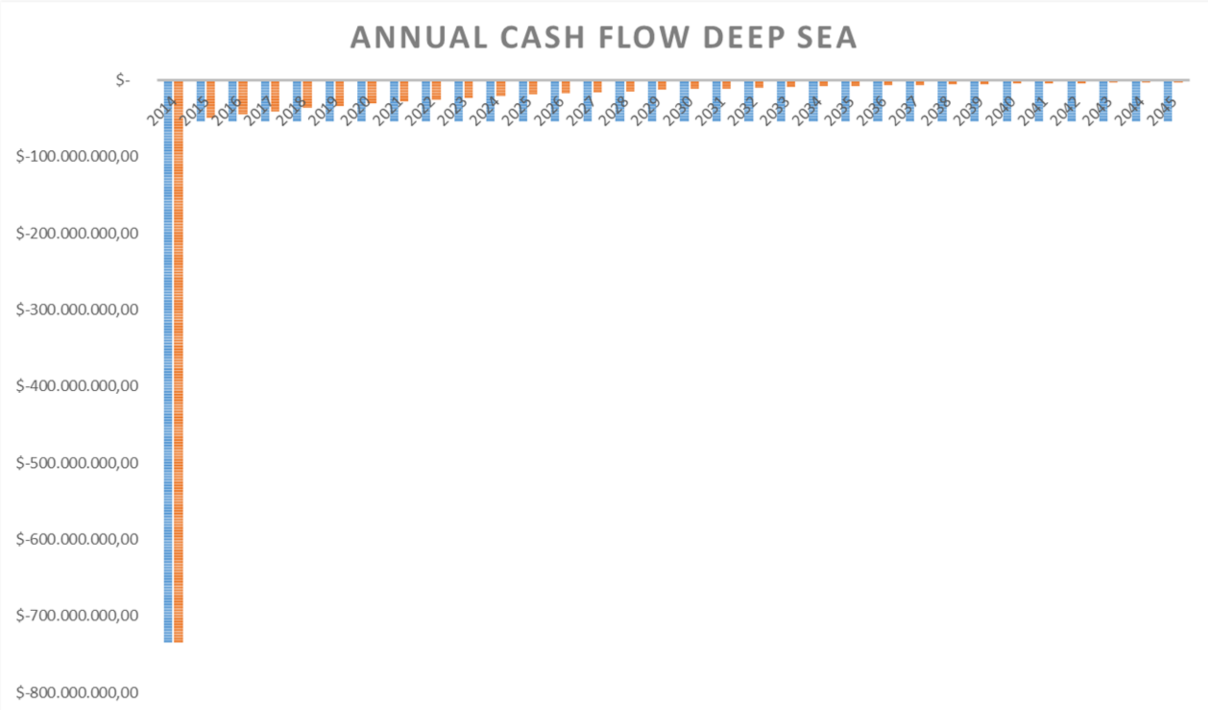

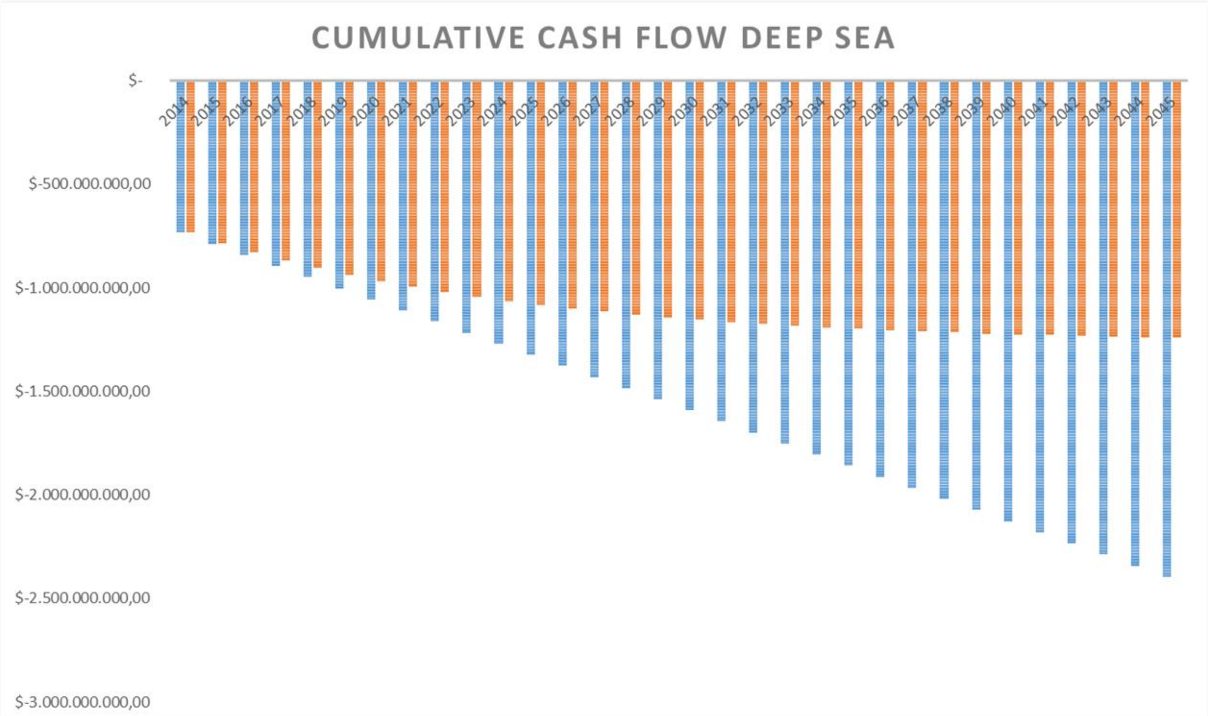

Figure B 4: The annual and cumulative cash flow of Pacific Ocean. For the NPV a discount rate of 10% is used.