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Life cycle assessment of electric power generation by wind turbines containing rare earth magnets

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Submission date: June 2015
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Department of Energy and Process Engineering

EPT-M-2015-102

MASTER'S THESIS

for

Student Christoffer Venås

Spring 2015

Life cycle assessment of electric power generation by wind turbines containing rare earth magnets

Livsløpsanalyse av produksjon av kraft med vindturbiner som bruker sjeldne jordarter

Background and objective

Wind power is the second largest contributor, next to hydropower, to global renewable electricity production. Furthermore, global installed wind power capacity is growing rapidly – the average growth rate over the last ten years is probably roughly consistent with achieving the 2°C climate target – and is expected to continue to grow in coming decades. Certain types of direct drive (gearless) wind turbines contain permanent magnets made of rare earth element (REE) alloys. Such gearless wind turbines represent a fairly small share of the current global wind turbine fleet, but the trend is towards increasing market share and several big wind turbine manufacturers are pursuing the development of such turbines. One advantage of wind turbine designs using REE magnets is that the nacelle weight is low relative to competing designs. Another touted benefit is enhanced reliability and reduced maintenance requirements. These benefits are considered to be particularly valuable for developments taking place offshore. On the other hand, there is considerable concern that mining and processing of RREs cause environmental damage.

Despite the growing market share of REE-containing wind turbines, existing environmental life cycle assessments (LCAs) of wind power uniformly study wind turbines not containing REEs. This leaves a noticeable gap in the account of environmental impacts of wind power, as it remains unclear and untested to what extent findings for conventional designs are representative of that for designs using REEs. Wind turbines with REE magnets exhibit lower total nacelle weight, which may indicate lower environmental impacts, but differences in material compositions also influence life cycle impact results, and besides the REE supply chains may cause unique environmental problems. This calls for comprehensive and consistent life cycle assessments to be performed in order to compare the environmental performance of wind turbines with and without REE magnets by different indicators.

The main objective of this thesis is to assess the life cycle environmental impacts of electric power generation by wind turbines containing REEs. Additionally, a secondary objective is the compare the environmental impacts of wind turbine designs with and without REEs. The work should build on and, where appropriate, modify, improve or extend previous LCA work on REE (by the student in project thesis, autumn 2014) and on wind power (by IndEcol researchers).

The following tasks are to be considered:

1) Briefly describe wind turbine technology basics and value chain, placing special emphasis on direct drive turbine designs and rare earth magnets.
2) Compile detailed life cycle inventory data for REE magnet production, and for a selected wind turbine configuration with REE magnet. Clarify important similarities or differences of this data compilation in comparison to previously published LCA work.
3) What is the most suitable method for life cycle inventory, a purely process-based method or a hybrid process- and input-output-based method? Briefly explain your methodological choice.
4) Conduct an LCA of electric power generation by wind turbines containing REEs.
5) Discuss the reliability and uncertainty of results and the implications of findings.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14 January 2015

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Preface

This master thesis is the final compulsory submission to complete my MSc degree in Energy and Environmental Engineering. The work was conducted at the Department of Energy and Process Engineering and at the Industrial Ecology Programme at the Norwegian University of Science and Technology (NTNU) during the spring semester of 2015.

First, I would like to thank my research advisor Dr. Anders Arvesen, together with my academic supervisor Prof. Edgar Hertwich, for guidance during the progress of this work. I would also like to thank researchers Astrid Røkke, Prof. Arne Nysveen, Zhaoqiang Zhang and Prof. Robert Nilssen at the Department of Electric Power Engineering at NTNU for invaluable feedback regarding the field of wind turbines.

Abstract

Direct-drive permanent magnet generator (DD-PMG) wind turbines are becoming a larger part of the growing offshore wind turbine market. The strong permanent magnets used, the NdFeB magnets, contains neodymium metal. The neodymium metal is a rare earth element (REE), and there are large environmental concerns regarding the mining and processing of the REEs. The research within the field is scarce. Consequently, there is a lack of knowledge of the environmental consequences of a shift away from the conventional gear-based turbine technology. In this thesis, a life cycle assessment (LCA) of electricity power production from offshore DD-PMG turbines was performed. To my knowledge, there are no previous LCAs of the DD-PMG turbines, thus the thesis will provide the first steps to fill this gap of knowledge.

To be able to compare the conventional and the DD-PMG technology, an acknowledged, existing life cycle inventory (LCI) of an offshore wind farm, consisting of conventional wind turbines, was used (Arvesen et al. 2013). The inventory was modified to represent a wind farm with DD-PMG turbines. The scope of the assessment included a detailed inventory of the production of neodymium metal, which was important to accomplish an evaluation of how the use of REEs affected the environmental performance of wind power.

In the assessment, it was found that the DD-PMG had less impact than the conventional design in 12 of the 13 included environmental categories. The increased electricity power production for the DD-PMG turbine was one main driver for the reductions, together with reductions because of a more compact nacelle. The omission of the gearbox led to a lighter, more streamlined nacelle configuration that turned out to be important for the results. In addition, there was less copper mass in the DD-PM generator. This caused reductions in the impact, especially in the toxicity and freshwater eutrophication categories. In these categories, we saw the highest reductions, which were in the range of 13-24 % for the process-based LCA results.

Excluding the foundation, the NdFeB magnet mass share is 0,46% of the wind mill construction. Thus, it is a small part of the total wind farm system, but does have a considerate impact in many of the categories. It is dominant for the marine eutrophication category, leading to an impact increase of 58 % from the conventional to the DD-PMG design. The relative share of the total impact related to the neodymium magnet is in the range of 2-6% for 10 of the 13 considered categories. A closer analysis showed that the use of copper was more critical than the use of NdFeB magnet material to the impacts in the *toxicity category group*. This indicates shortcomings of the neodymium metal inventory, as one would assume that these impacts at least would be similar for the two materials. More data based on the empirical practice of neodymium metal production is a prerequisite to develop the environmental research within the field. The neodymium metal inventory does show robustness for more fossil energy-dependent categories, like climate change, where the use of NdFeB turns out to be more critical than copper.

A benefit of the DD-PMG turbines is claimed to be an increased reliability compared to the conventional technology, since critical gearbox failures are avoided. In a sensitivity analysis, it is shown that a decreased downtime, together with less maintenance activities from marine vessels, gives a potential of even higher reductions of the environmental impact.

The results from the thesis shows that the DD-PMG design is beneficial from an environmental point of view. The advantages of reduced weight in the nacelle and increased electricity production in the DD-PMG design outperforms the disadvantage of using NdFeB magnets.

Sammendrag

Direktedrevne vindturbiner som benytter en permanentmagnetgenerator, såkalte DD-PMG-turbiner, inntar en større og større del av det offshore vindturbinmarkedet. De sterkeste og mest populære magnetene i bruk, NdFeB-magnetene, inneholder metallet neodymium. Neodymium er et metall som inngår i gruppen av sjeldne jordarter (REE), og det er bekymringer knyttet til de miljømessige konsekvensene av utvinning og fremstilling av slike sjeldne jordartmetaller. Det er lite forskning på området, og dermed lite kunnskap om konsekvensene av et skifte fra den konvensjonelle, girbaserte teknologien til DD-PMG-teknologien. I denne masteroppgaven ble det utført en livssyklusanalyse (LCA) av elektrisitet produsert fra offshore DD-PMG-vindturbiner. Så vidt jeg vet, finnes det ingen tidligere livssyklusanalyser av disse turbinene. Dermed vil denne oppgaven gi de første innsiktene til de miljømessige virkningene av det som er sagt til å være fanebæreren i utviklingen av vindturbiner offshore (Siemens AG 2013).

For å kunne sammenligne vindkraft fra konvensjonelle og DD-PMG-turbiner, ble det brukt et eksisterende, anerkjent livsløpsinventar (LCI) av en offshore vindmøllepark med konvensjonelle turbiner (Arvesen et al. 2013). Inventaret ble modifisert slik at det fremstod som en vindmøllepark med DD-PMG-turbiner. Innenfor rammen av oppgaven var det også ønsket et detaljert inventar av sjeldne jordarter. Dette var viktig for å kunne vurdere hvordan bruken av REE påvirket miljøbelastningene knyttet til vindkraft. I analysen fant vi at DD-PMG-turbiner hadde mindre påvirkning enn konvensjonelle turbiner i 12 av de 13 undersøkte miljøkategoriene. Den økte elektrisitetsproduksjonen og en lettere og mer kompakt nacelle førte til disse reduksjonene. Det viste seg at en lettere nacelle, på grunn at man utelater girkassen i DD-PMG-designet, var viktig for resultatene. I tillegg var det mindre bruk av kobber i DD-PM-generatoren. Dette reduserte særlig miljøpåvirkningene i kategorier for toksisitet- og ferskvannseutrofiering. I disse kategoriene var reduksjonene størst, 13-24%, for (de prosessbaserte) LCA-resultatene.

NdFeB-magnetene utgjør kun 0,46% av vekten til vindmøllekonstruksjonen, om vi utelater fundamentmassen til konstruksjonen. Den har allikevel forholdsvis høy påvirkning på resultatene. Særlig for kategorien for marin eutrofiering, hvor fremstillingen av neodymium fører til en økning i miljøbelastningene på 58%. Andelen knyttet til NdFeB-magnetene er fra 2-6% av resultatene i 10 av 13 miljøkategorier. Nærmere undersøkelser viser at bruken av kobber er viktigere for resultatene enn NdFeB for miljøbelastinger i toksisitetkategorigruppa. Dette kan indikere at inventaret for neodymiummetallet ikke dekker de reelle miljøbelastningene, siden man i utgangspunktet skulle tro at belastningene i det minste var like for de to metallene. Større datatilgjengelighet basert på empirisk forskning er en forutsetning for framtidig utvikling av forskningen innen feltet. I andre kategorier, som påvirkes mer av bruken av fossil energi, ser vi imidlertid at inventaret er robust.

Mindre vedlikehold og færre driftsstans hevdes å være en fordel for DD-PMG-turbiner, siden man unngår de kritiske feilene på girkassa. Resultatene fra denne oppgaven viser at mindre nedetid for turbinene, samt mindre bruk av skipsfartøy til vedlikehold, gir et potensiale for enda høyere reduksjoner av de miljømessige påvirkningene.

Ved en total vurdering av miljøbelastningene, viser resultatene fra denne oppgaven at DD-PMG-designet er fordelaktig. I denne sammenhengen er ulempene ved å bruke NdFeB-magneter mindre enn fordelene av en lettere nacelle og økt elektrisitetsproduksjon.

Contents

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List of abbreviations

DD-PMG	Direct drive permanent magnet generator	*-Type of generator design*
DFIG	Doubly Fed Induction Generator	*-Type of (conventional) generator design*
FDP	Fossil fuel depletion potential	
FEP	Freshwater eutrophication potential	
FETP	Freshwater ecotoxicity potential	
FPC	Full power converter	*-Used in DD-PMG design*
GWP	Global warming potential	*-Used for the climate change category*
GHG	Greenhouse gas	
HREE	Heavy rare earth metals	
HTP	Human toxicity potential	
LREE	Light rare earth metals	
MEP	Marine eutrophication potential	
METP	Marine ecotoxicity potential	
Nd	Neodymium	
NdFeB	neodymium-iron-boron	*-The alloy of the NdFeB (permanent) magnet*
ODP	Ozone depletion potential	
PMFP	Particulate matter formation	
POFP	Photochemical oxidant formation	
PM	Permanent magnet	
pp	Percentage points	
Pr	Praseodymium	
PRC	Partial rated converter	*-Used in conventional design*
REE	Rare earth elements	
REO	Rare earth oxides	

REM	Rare earth metal	*-Used about REE in metal form.*
RE	Rare earth	*- Succeeded by a suitable noun*
SPA	Structural path analysis	
TAP	Terrestrial acidification potential	
TETP	Terrestrial ecotoxicity potential	

1 Introduction

"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems."

This is the clear message from the Intergovernmental Panel on Climate Change (IPCC) to policymakers in the summary of their recently published fifth assessment report (IPCC 2014). With a quarter of the greenhouse gas (GHG) emissions in 2010 being from the electricity and heat production sector, development of renewable electricity generation has been seen as a key pathway for mitigation. Leading in this development is the wind energy technology, being the second largest renewable electrical generation technology after hydropower (Edenhofer et al. 2011). The installed capacity is rapidly growing, and innovation is high within the industry, making it hard to assess the full potential of wind power for the global energy system (Edenhofer et al. 2011).

An important part of this unknown potential of wind power lies offshore. Because of the stronger and more reliable winds and the vast, empty areas available, the wind power industry is now looking to the oceans (Wiser et al. 2011; Siemens AG 2011). Far away from people, the visual and noise annoyance from the wind turbines is no longer an issue, so the sizes of the turbines and windmill parks can grow to the technological constraints (Lynn 2012; Tabassum et al. 2014).

A challenge for the wind industry in general is the high cost of energy. For offshore wind energy, the costs are even higher. Especially the installation and maintenance logistics are difficult and increases costs (Wiser et al. 2011). The direct-drive (gearless) technology is emerging as a promising technology to increase the reliability and bring down the maintenance costs of large wind turbines (Aleksashkin & Mikkola 2008; The Switch 2014). A more compact nacelle and increased energy production relative to the conventional turbines designs are other proclaimed benefits of the direct-drive design (Fairley 2010; Kurronen et al. 2010). In the most promising direct-drive designs, strong permanent magnets are essential components of the generator. The strongest and most used of these are the NdFeB magnet that contains a rare earth element (REE) called neodymium (Nd) (Brown et al. 2014). The rare earth elements are critical metals, and there are great concerns regarding the environmental impacts of mining and processing of REEs (Schüler et al. 2011; Lee Bell 2012; Ali 2014).

The main objective of this master thesis was to perform a life cycle analysis of electric power generation by wind turbines containing REEs. The offshore direct-drive technology containing the NdFeB permanent magnets is the emerging technology at the time, and is the most relevant for the analysis. A second objective was to compare the environmental impacts found with a conventional wind turbine design, to provide new insights of the environmental performance of this new wind turbine segment.

In order to perform a complete assessment, detailed data for the mining and processing of the rare earth metal called neodymium was needed, as well as for the production of NdFeB magnets. It is for these productions there are the highest uncertainties concerning environmental damages. The environmental and other processing data are scarce and somewhat inaccessible, thus an in-depth understanding of these topics is needed in order to develop a detailed model for this part of the assessment. One important secondary objective of the thesis was therefore to assess the neodymium metal and NdFeB magnet production.

To my knowledge, this master thesis will be the first contribution of LCAs of wind power generation using the direct-drive NdFeB permanent magnet generator design. It will increase the understanding of how the environmental impacts of these turbines compare to the conventional turbines. The thesis will give the first insights related to the environmental impact of what can be an important piece of tomorrow's energy system.

1.1 Structure of the thesis

This introduction, which is chapter 1 of this thesis, ends with a short presentation of important references considered in the study.

The second chapter is the background theory. The first section, section 2.1, introduces the reader to the wind turbine technology. It provides the reader of an understanding of why the research of offshore wind turbines and direct-drive turbines is important, and provides a basis for the reader to understand the technical choices done in the inventory of the thesis (in section 3.5). Section 2.1 includes differences between the conventional and direct-drive technology (section 2.1.3) and maintenance perspectives (section 2.1.4).

Section 2.2 is background theory of the NdFeB magnets used in the investigated wind turbines.

Section 2.3 will deal with the rare earth elements. As the research field is complex, a thorough literature search was made in order to prepare the desired detailed life cycle inventory. This section gives the reader insights to the state of the rare earth industry. Since the common scientist does not have a deep knowledge of the field, and theory of the rare earths is somewhat inaccessible and scattered, this section is comprehensive. It gives the reader a chance to understand the diversity of the field and the need and motivation for research within the field. Hopefully, it will give an understanding of challenges faced and choices made upon construction of the inventory (in section 3.1), and clarify the limitations of the study. The section also presents the option of rare earths processing chosen for further investigation, the Bayan Obo mine and Baotou processing plant (section 2.3.4). In section 2.3.5, the various kinds of environmental concerns related to the rare earth metals is presented.

Materials and methods used for the assessment is presented in chapter 3. Section 3.1 gives a brief introduction to the field of LCA, and key references are given to readers that are unfamiliar with the technique. It includes a presentation of the specific methods and frameworks used in the study.

Before details are presented, the section 3.2 will give a picture of the overall scope of the study. Presentations of the goal, scope and life cycle inventory (LCI) of the three parts of the study comes next. Beginning at the starting point in the value-chain of the power production, the section for the neodymium metal comes first, in section 3.3. We continue with the goal, scope and inventory of NdFeB magnet production in section 3.4. The detailed materials and methods for the complete wind farm producing electricity is in section 3.5.

Results and the discussion of them is provided together in section 4. It is in the same sequence as the previous chapter. Thus, a detailed results and discussion section of the neodymium metal is first in section 4.1. This gives a proper evaluation of environmental concerns regarding rare earth elements processing. Then follows the results and a discussion of the assessment of NdFeB magnets (section 4.2). At last, in section 4.3, the results and discussion of the wind park follows, with a focus on highlighting the differences in environmental impact of the two investigated wind turbine designs.

Section 5 contains the conclusion of the study. In section 6, a list of references is provided.

For the interested reader, the processing of the rare earth mineral ion-adsorption clay can be found in appendix A.1. The files used in the Arda analysis is found to fit better in a Excel format than the appendix, and can be sent to the interested reader by contacting christoffer.venas@gmail.com.

1.2 Important references and previous work

Sprecher et al. (2014) performed an LCA of NdFeB magnet production, and it has been an important reference during the work of the neodymium metal and NdFeB magnet inventories. It is the most comprehensive and transparent of the LCAs considered. Several of the neodymium processing stages in the current assessment are similar to the stages used in work by Sprecher et al. In addition, it provided some data to the current inventory, which will be referenced in the materials and methods chapter 3. It was the only detailed reference found that covered NdFeB magnets, and consequently was a basis for most of the NdFeB magnet inventory.

The book "Extractive Metallurgy of Rare Earths" of Gupta & Krishnamurthy (2005a) is a detailed book about REEs. It was very useful for the background theory of the thesis. It contains much information about processing of the rare earths. However, many references in the work are old. E.g. the Bayan Obo (REE) process descriptions in Gupta & Krishnamurthy (2005a) are based on 30 year old data. The high level of detail in the book at occasions also rise uncertainty between if the practices are used marginally or commonly within the commercial industry. Gupta & Krishnamurthy (2005a) provides detailed descriptions, but does not present quantified process data.

The report "Study on Rare Earths and Their Recycling" from Schüler et al. (2011) on the other side does include some newer references, most notably information from a couple of references in Chinese. It is also the work with most detail on the environmental implications related to the industry. It does give a good overview of the industry, including ore and reserve data and other interesting details for several current and future production sites. However, the report does not go into detail on the production process or specific process data. It includes some sporadic environmental data.

"Material and Energy Requirement for Rare Earth Production" of Talens Peiró & Villalba Méndez (2013) has the most specific data of the studied literature. The article is a step in the right direction of improving data quality. It includes estimates for the energy requirements for all processing stages of RE metals. It also gives a detailed description of the different materials used throughout the processing scheme. However, material requirements are only quantified for the extraction stage. The beneficiation with flotation of the Bayan Obo ore is not treated, and the paragraph about the solvent extraction stage is confusing, especially regarding the transparency of the assumptions undertaken for data calculations.

Some quantified data for production and environmental stressors can be found the LCA articles about the RE production. "Life cycle inventories of chemicals" of Althaus et al. (2007) is the earliest of the LCAs considered. This was a work commenced to make a dataset for the Ecoinvent database v2.2. The study is transparent – and for this reason has been important during the construction of the neodymium metal inventory. One limitation is that it tries to be generic for all REE production, and therefore end up with describing a non-existing production scheme. The data for some of the stages is very poor, and the mining and beneficiation stages are based on phosphate mining. The dataset does not include the last reduction stage to form metals from the rare earth oxides, and only briefly treats the beneficiation and extraction stages. Sprecher et al. (2014) developed much of their inventory based on the work by Althaus et al (2007).

Nuss & Eckelman (2014) present an overview of the cradle-to-gate environmental burdens of 63 metals (plus helium) in their major use forms. The work on rare earth metals (REEs) was only a minor part of the study. For REEs, they only did some changes of the price allocations of from the work by Althaus et al. (2007). The REEs were not reduced to metals from their oxide form. There was given new insights for other metals, but not for REEs in this article. It was therefore not used extensively in this work.

The "Life Cycle Impact of Rare Earth Elements" by Koltun & Tharumarajah (2014) is a detailed assessment of the Bayan Obo production in China. The article is not transparent enough to be useful in a high degree for this assessment. Emphasis is put on comparisons of impact between the different REEs. This was based on interesting approaches to allocation issues. It did provide some insights on allocation issues and included the reduction stage.

The secrecy of the processing practices within the industry is an obstacle for increasing the data availability, as noted by Talens Peiró & Villalba Méndez (2013). As a result, the major part of research data is only available for the Bayan Obo and the Mountain Pass mine. This existing literature in English is based on a small number of older sources. Data availability is a limitation of the current study.

The recently published article "Life-Cycle Assessment of the Production of Rare-Earth Elements for Energy Applications: A Review" of Navarro & Zhao (2014) gives a clear picture of the current state of the literature regarding LCAs of rare earth elements. It was published too late to be of great importance of this work. However, after working on the topic, I feel it gives a realistic snapshot of the issues of the research field, and is a must-read for the REE-interested reader.

An assessment of neodymium metal was a project work performed in the autumn semester in 2014. This work was revisited and revised during the work of this master thesis. In particular, there was done some important work to identify additional stressors from the processing of rare earths.

The acknowledged and detailed inventory of the windmill park studied by Arvesen (2013) is used for constructing large parts of the current windmill inventory. The published article was a case study of a proposed wind farm Havsul 1 in western Norway. They used a hybrid LCA approach, and placed emphasis on installation, operation and maintenance of the turbine. As most LCAs at the time gave little attention to these aspects, the article filled a gap in the contemporary knowledge. They found offshore installation and maintenance activities caused 28% (10 g CO2 eq. /kWh) of the total climate change impact. The use of marine vessels for these activities was a large contributor to the impact. Also in environmental impact categories like marine eutrophication, acidification, particulate formation and photochemical ozone formation the impact was large, from 31% to 45% of total impact indicator values.

The turbines studied by Arvesen et al. were conventional turbines, and the turbine part of the inventory was rebuilt to consist of direct-drive permanent magnet generator (DD-PMG) turbines.

2 Background

2.1 Wind turbine technology

2.1.1 Introduction to wind energy technology

Before the 20th century, most windmill technologies were simple. They were used for grain grinding or water pumping purposes. The first reported designs are from Persia (200 BC). The wind mill was developed in Europe from 14th century, with a later development in the Americas. From 1850 to 1970 over 6 million wind mills were installed in the Central USA for water pumping purposes. (Lynn 2012; Hansen 2008; Kaldellis & Zafirakis 2011)

In 1888 the first electric wind turbine was created in the US by Charles Brush (Lynn 2012). Further developments followed, and the affordable Jacobs turbine from 1925 was popular in remote areas in the US. It produced small amounts of DC electricity to a battery at varying wind speeds, and the simple mechanism was reliable enough to last for several years without maintenance (Carlin et al. 2003).

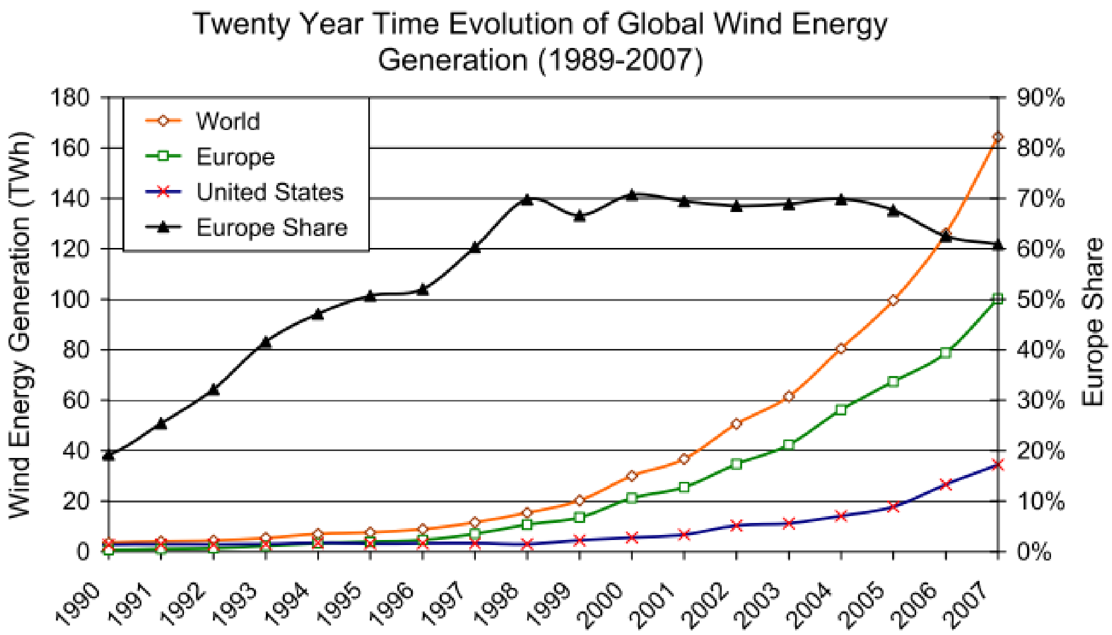

Figure 2-1, Time evolution of global and European wind power capacity and wind energy generation (Kaldellis & Zafirakis 2011)

However, in the following decades there was little interest in the wind turbine technology. Fossil energy, together with nuclear energy, provided a more stable supply and was preferred (Tabassum et al. 2014). It was not until after the 1973 oil crisis that renewable energy again gained attention. In the 1980s, the US government funded large wind farm projects, centered in California (Kaldellis & Zafirakis 2011). The installations of wind turbines in Europe increased steadily, especially in Denmark. This development lead to great technological leaps in the wind turbine technology in the 1990s and beyond. This made the turbines larger and larger, being able to produce electricity from the turbines at higher power, simultaneously decreasing the energy cost of wind power. This increased ability of the turbines to harvest the energy efficiently in the wind flow, i.e. the increased capacity factors, led to a boom in the installed capacity throughout the first decade of the new millennium (figure 2-1). At the same time, the climate change debate intensified. This lead to increasing governmental funding of green solutions, especially in some key countries in Europe. This contributed to the developments of the wind turbine industry.

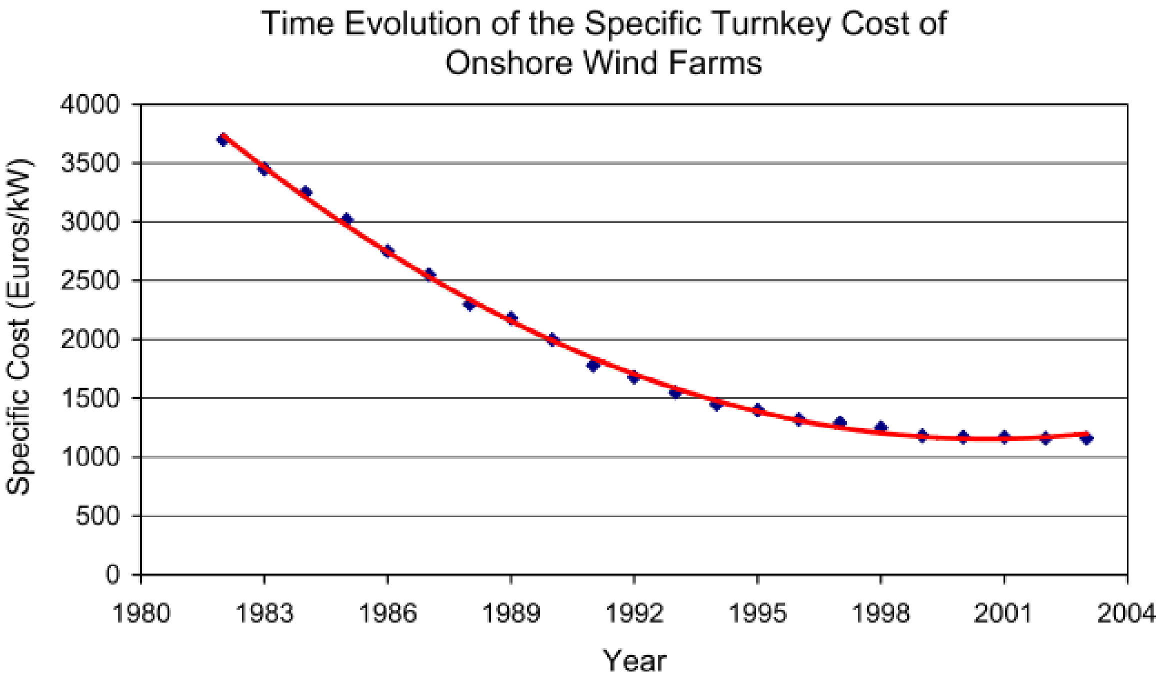

Figure 2-2, Time evolution of the specific turnkey cost. Source: Kaldellis & Zafirakis (2011)

Wind power is now seen as a key solution for a "green shift" away from fossil-based power generation. Contrary to fossil-based solutions, the uncertainty of prices and access to fuel is non-existent. As the investment and operational costs are decreasing (figure 2-2), the wind power solutions are gaining attraction for a stable and green supply of energy in the modern world.

The majority of the wind turbines today have a horizontal design, with a three-blade *rotor* as shown in the figure 2-3 (Kaldellis & Zafirakis 2011). On top of the *tower*, the *nacelle* and the *rotor blades* are situated. The rotor blades are the largest moving part of the wind turbine. The blades are the aerodynamic counterpart of the wings of an airplane. As winds flow past the rotor blades, the lift force will indeed lift the blades, initiating their rotation. The connected *low-speed shaft* will rotate at the same speed as the rotor blades, and is dependent on the wind speed.

In a conventional wind turbine design, a *gearbox* couples the low-speed shaft with a *high-speed shaft.* This is the shaft connected to the *rotor of the generator*. The generator also consists of a *stator*, being the other of these two active parts in the generation of electricity.

These components make up the drivetrain components (the shafts, gearbox and generator). They are situated inside the *nacelle*, which is the housing of these key components. The nacelle is situated on top of the *tower*, one of the important structural elements of the windmill.

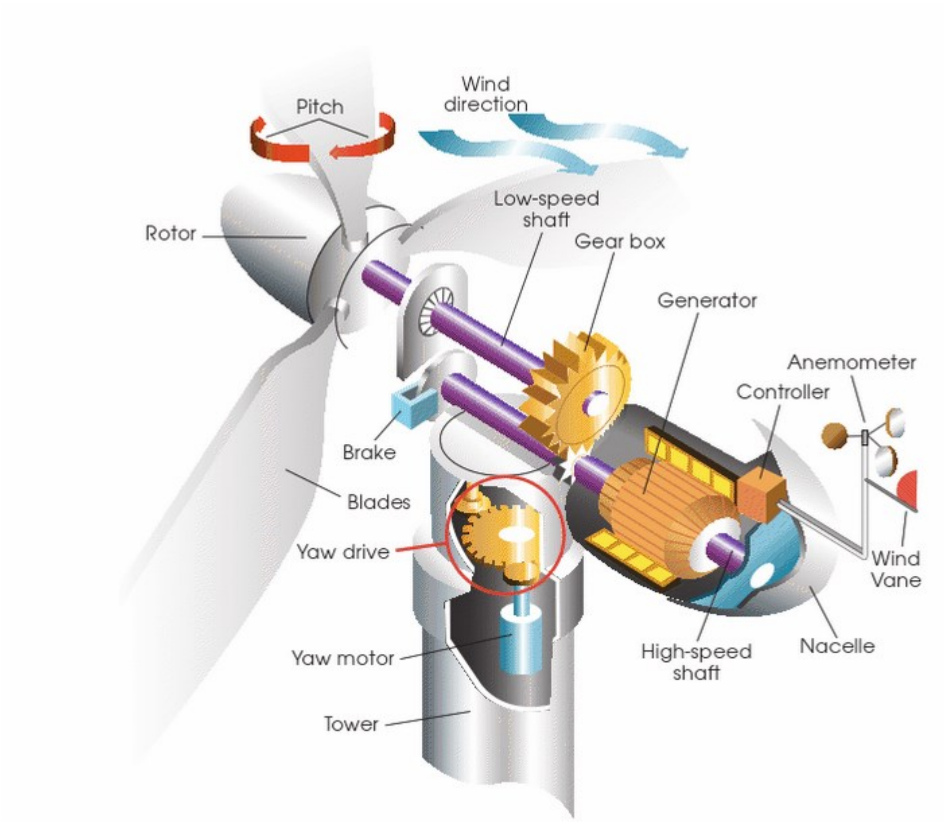

Figure 2-3, Graphical breakdown of the typical components of a wind turbine. Source: Lynn 2012.

The development today is that the power size of the turbines increases. A main motivation is that the cost per kWh in general decreases with the turbine size. Thus, the dimensions of the components of the modern wind turbines is rapidly increasing. The potential energy that can be extracted in a wind turbine depends on the cross-sectional area the rotor blades can sweep. This means that the size of the rotor blades is increasing as the turbine size increases. This leads to a tower height increase as well.

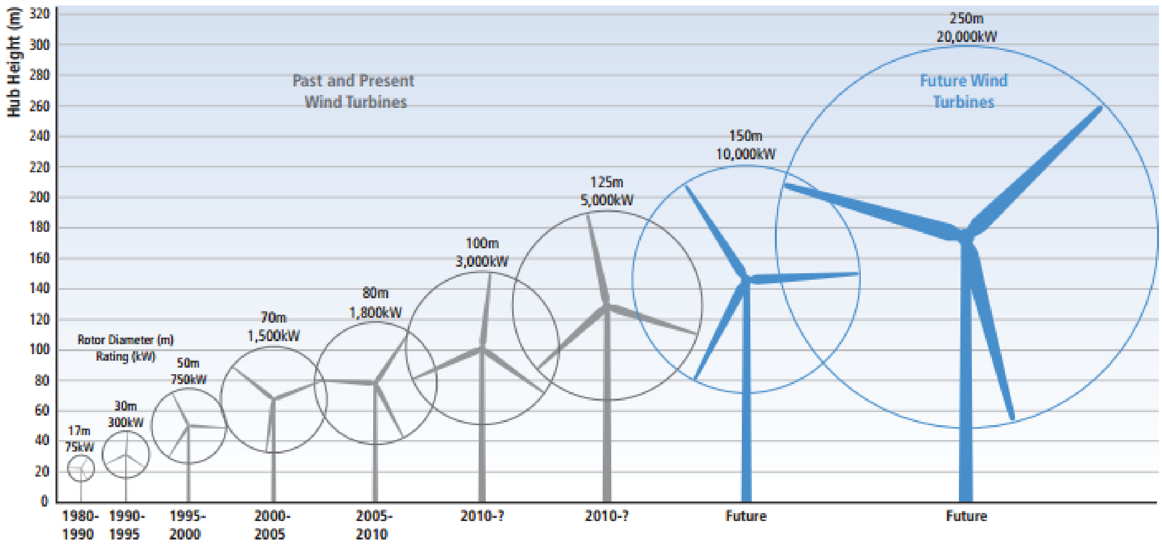

Figure 2-4, Development of wind turbine sizes from 1980 to 2010, for both rotor diameter and power size. The figure includes future scenarios. Source: Wiser et al. (2011)

Another reason for increasing the tower height is that the wind velocities are higher at higher altitudes. In the atmospheric boundary layer close to the surface of the earth, the wind increases rapidly with altitude. Typical towers are 50-125 m for onshore wind turbines today (Wiser et al. 2011). The rapid development of the wind turbine dimensions can be seen graphically in figure 2-4.

Several wind mills are situated together in *a windmill park* (also called *wind farm*), and a specific electrical system is designed for this windmill park. The purpose is to connect the wind turbines to the electrical grid. The exact configurations depends on the generator type used for the wind turbine design. Often, every generator is independently connected to a *converter.* It is used to control and match the generated electricity with the grid properties, like the frequency. To minimise electrical power losses during transmission, the voltage is increased before transmission from the wind park. *Transformers* are used for this purpose.

2.1.2 Offshore designs

The offshore wind adventure started in the shallow waters outside Vindeby, Denmark in 1992 (Lynn 2012). It is the North Sea that has been the hotbed for offshore development, benefitting from the experiences and expertise of the waters from the oil and gas sector. In 2013, the European offshore wind turbines supplied 24 TWh of electricity, but this is expected to increase to 140 TWh by 2020 (Jacobsson et al. 2013). The installed offshore wind capacity in 2012 is displayed in figure 2-5.

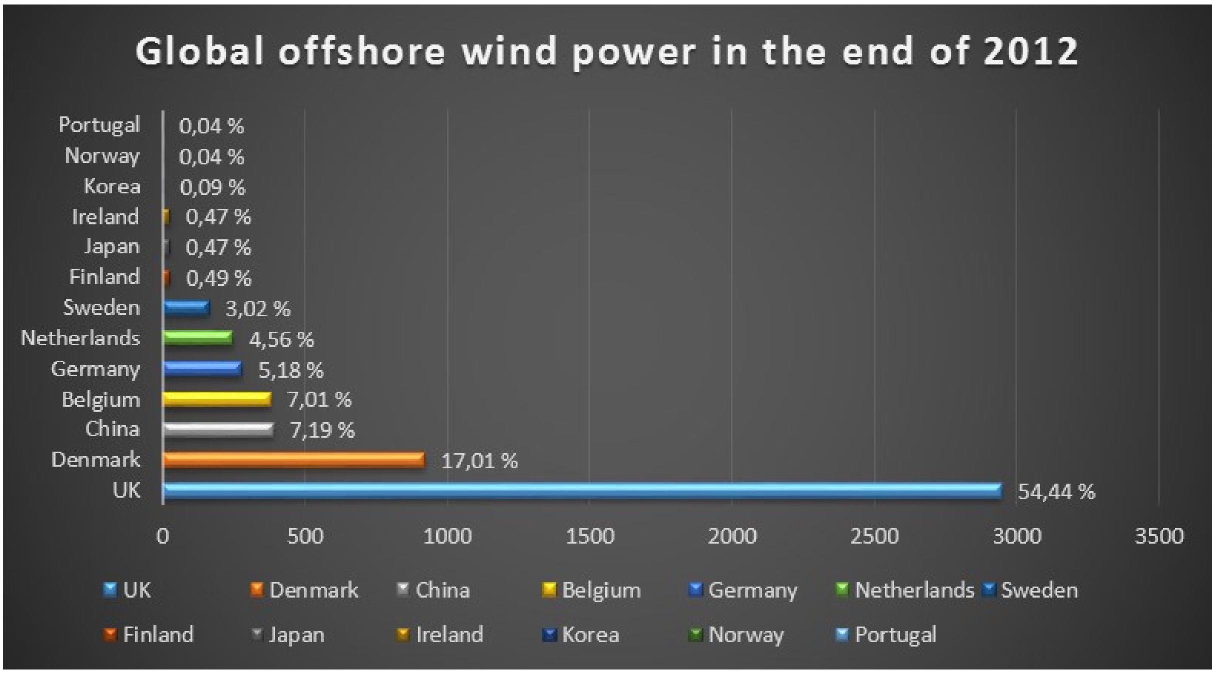

Figure 2-5, Installed offshore wind power capacity, cumulative by country (in MW). Data is compiled from GWEC - Global Wind 2012 Report (2012)

There are several reasons for the urge to move the wind power production offshore. There is a potential for higher and more stable electricity production as the winds are stronger and more consistent offshore (Wiser et al. 2011; Siemens AG 2011). Air density is highest at sea level, and higher air density is will increase the potential power output of a wind turbine. There are also vast amount of unused area at the continental shelves (Lynn 2012; Tabassum et al. 2014; Wiser et al. 2011). The visual and noise pollution from the turbine cease to be a problem, thus the constraints for maximum turbine sizes will only be technological. As the constraints are few, the turbines are larger than onshore turbines, and the average offshore turbine was 3,7 MW in 2014 (Corbetta et al. 2014). The average wind farm is also large, and was at average 368 MW in 2014.

As of today, the offshore wind technology is still immature, and large technological developments are expected. The wind mill parks are moving further offshore, with the average distance to shore being 32,9 km (Corbetta et al. 2014). To go even further from shore, developments of the foundations are needed. The technological substructure types used today are founded in the seabed, and offers water depths up to 40-50 meters. Most of the capacity today is in the depths of 0-30 m. To go beyond 50 m deep waters, floating turbines is said to be the technological solution (Genachte et al. 2013). The research activity is high, with two floating test-turbines already grid-connected (Corbetta et al. 2014).

The challenges of offshore wind turbines are the harsh, wet weather conditions offshore, demanding a high product quality. The need for special marine vessels and helicopters for installation and maintenance complicates the offshore operation. High quality of the substructures is also required for offshore wind turbines. These challenges lead to higher energy costs of offshore wind power generation relative to the onshore production (Wiser et al. 2011). Maintenance issues of the offshore wind turbines will be covered in section 2.1.4.

Converters and step-up transformers are mostly installed connected to each turbine (Gjerde & Undeland 2012). The turbine-individual transformers will have a medium voltage output common for all the turbines in the windmill park (Birkeland 2011). There will be at least one transformer station in the windmill park to get high voltage electricity suited for transmission over longer distances, with the need of infrastructure for this HV transformer station. However, one important point is that in offshore wind turbine designs the turbine-individual converters and transformers also must be situated inside the nacelle, contrary to the onshore turbine shown in figure 2-3. This leads to a potential increase in the weight of the nacelle.

The transmission of the electricity is also more complicated offshore. Since transmission by cables on the seabed is preferred, a challenge is the higher costs of this compared to onshore transmission. Transport by high voltage AC (HVAC) cables is often used for transmission within the windmill park, as it is cheaper for short distances. For the transmission from the site to the onshore grid, both HVDC and HVAC cables can be used, with the HVDC cables being preferred for long distance transmission (Birkeland 2011; Kaldellis & Zafirakis 2011). The infrastructure of the high voltage transformer station is also more costly and complicated, due to the wet environment.

Other implications of moving the wind generation offshore is the increased stress on the marine environment. Tabassum et al. (2014) points out several potential environmental impacts from the offshore wind farms:

- *"Acute noise-related impacts during construction phase, especially due to driving, drilling and dredging operations.*
- *Disturbance due to intensive marine and aerial transportation activities during exploration, construction and maintenance.*
- *Generation of polluted sediments during construction and their re-suspension.*
- *Collisions of birds and other organisms with offshore wind farm (OWF) structures.*
- *Creating of the artificial reef effect by the presence of structures, individually and in arrays, with concomitant impacts on biodiversity.*
- *Chronic, long-term, impacts due to continual operational noise and vibrations emanating from OWF.*
- *Electromagnetic impacts arising from underwater cable networks that may interfere with animal navigation.*
- *Thermal impacts that may aggravate the impacts of other stressors on the benthos.*
- *Impacts of episodic traffic increase for troubleshooting.*
- *Impacts during physical decommissioning, particularly the steps which would involve the use of explosives"*

2.1.3 Direct-drive designs versus conventional DFIG turbine design

As reliable turbines is a key element for lowering the costs of offshore wind power, the popularity of direct-drive turbine design is increasing. Schüler et al. (2011)states that about 14% of the new wind turbines installed are direct-drive wind turbines. Hoenderdaal et al. (2013) points out that the increasing installed offshore wind power can give a market share of 35-50% to direct-drive wind turbines by 2050. The drivetrain configuration itself is very different from the previously described conventional design, shown in figure 2-6, allowing for lower maintenance and operation costs (Aleksashkin & Mikkola 2008).

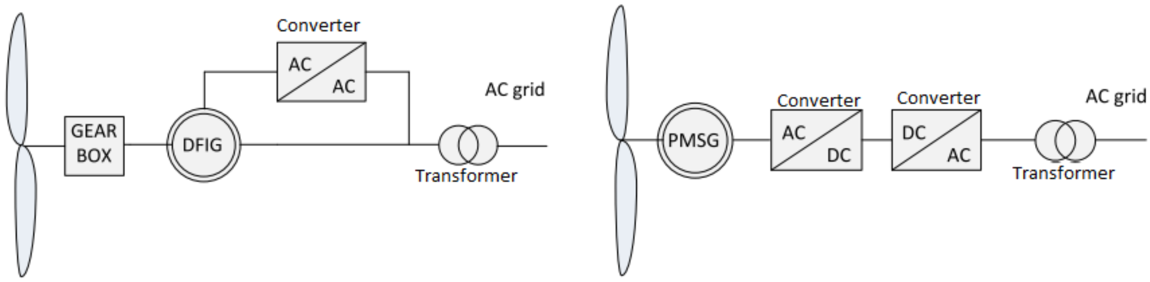

Figure 2-6, Schematic difference of the classical drivetrain designs of PM(S)G vs DFIG designs. Source: Iversen et al. (2013)

All differences stem from the use of a different type of generator, the permanent magnet synchronous generator (PMG). The most popular conventional technological option today is a double fed induction generator (DFIG), with a share of 50% of the installed wind turbines today being DFIGs (Gjerde & Undeland 2012; Aleksashkin & Mikkola 2008; Carroll et al. 2014).

In induction generators like the DFIG, the excitation field is normally provided by feeding a small (AC) current to (copper) coils in the rotor of the generator. The (electromagnetic) rotor needs to have a higher speed than the synchronous speed to induce a current in the stator winding, thus generating electricity. This synchronous speed is dependent on the coil and (fed) AC current properties. The electrical induction motors need a high rotational speed to produce power (1000-2000 rpm, Kurronen et al. 2010), so a gearbox is needed in these conventional configurations to increase the speed of the rotor inside the generator. The gearbox is also the component that is most lightly to fail during operation lifetime. The reliability of the designs will be discussed more in section 2.1.4.

Permanent magnet generators are self-excavating. The strong magnetic properties of the permanent magnets make it possible to induce a current in the stator at drastically lower speeds. This eliminates the need for a gearbox, thus increasing reliability of operation. The magnetic field and the rotor operate at the same (synchronous) speed. The torque of the generator must still be high enough at the low speeds, hence the size and weight of the generator itself will increase.

There are half as many parts in a PMG than a DFIG (Fairley 2010), since an induction generator needs slip rings or contact brushes. The need of excitation power reduces the efficiencies of the DFIG, especially when production is lower than the fully rated power output. The DFIG turbines can only produce electricity when wind speeds allow the relative rotor speed to be from 0,54-1 (relative to the rated speed). The PMG can produce electricity in the relative speed range of 0,2-1 (Kurronen et al. 2010). As a result of this operational flexibility, the increased annual energy production is indicated to be 8,5% higher for PMG at an average wind speed of 5,4 m/s. It would be 3% larger for an average wind speed of 8,2 m/s (Kurronen et al. 2010).

As seen in figure 2-6, the converters used are different. The DFIG has a proportionally rated AC/AC converter, a partial-load converter, to control the excitation of the machine, as parts of the power are fed directly to the grid.

The PMG has a full-power converter (Gjerde & Undeland 2012). It is the same electronics used, but the full-power converting is preferred from a grid compliance point of view, according to the PMG manufacturer The Switch (2014), compared to the partial power directly transmitted to the grid. However, there are three times as many power modules used in the typical FPC converters (18) than the partial-load converters (6), which might lead to higher failure rates on the converters (Fischer et al. 2015, elaborated in section 2.1.4).

There are several designs for permanent magnet generators with gearboxes. Solely direct-drive designs will be considered in this thesis.

2.1.4 Maintenance perspectives regarding offshore direct-drive wind turbines

As stated in section 2.1.2, for offshore wind power plants, the operation and maintenance (O&M) is more complex than for the onshore plants. Evidently, the accessibility is a big challenge for maintaining a high availability for offshore wind parks. The logistical complexity rises as the parks move further from shore, to more distant locations. The daily control of the operation of the turbines is performed from onshore locations, to reduce the need for offshore operations (Birkeland 2011). The wet environment with harsh weather conditions at site can cause problems when performing maintenance missions. Immediate access to appropriate marine vessels, or helicopters in rough weather conditions, is crucial for maintaining a low downtime (Shafiee 2015). The O&M costs are 20%-35% of the lifetime power generation cost, being around 10% for onshore wind power (Gray & Watson 2014; Shafiee 2015). Reducing these costs are crucial for the profitability of offshore power generation. Arvesen et al. (2013) find in their analysis that the maintenance phase is important for the environmental impacts from wind turbines. They find it to be related to 14% of the total carbon footprint, when considering the whole life cycle of the wind power generation. They also find that the use of marine vessels during the installation phase is important for the environmental impact from offshore wind turbines.

Failure rates and downtime for DD-PMG vs DFIG

The large wind turbines preferred offshore operate at lower speeds. For conventional WT technology, this leads to a more complex and larger gearbox. According to Scott Semken et al. (2012) a four-stage gearbox might be required, thus increasing mechanical losses. In addition, the gearbox is a critical component regarding reliability. Reliability is expected to decrease with the increasing size and complexity of the component. Gray & Watson (2014) points out the expensive and time-consuming maintenance required for gearboxes. They find the gearbox to be responsible for up to one third of the lost turbine availability. Crabtree (2012) states that "the gearbox and generator respectively contributed only 6.7% and 2.8% of total stops but 55% and 15% respectively of the downtime". The high downtime related to the generator is therefore one of the main motivations for developing the direct-drive technology.

Some references indicate that the failures from converters will be higher for the full power converter (FPC) used in the PMG direct-drive wind turbine than the partial converter (PRC) used in conventional turbines (Carroll & Mcdonald 2013; Echavarria et al. 2008; Spinato et al. 2009; Fischer et al. 2015). Carroll & Mcdonald (2013) states that the FRC will have failure rates 2,2 times higher than the partial-load converter. Fischer et al. (2015) find that there is a higher failure rate for FPCs, but that divided by the number of power modules in the converters, which are higher in the FPCs, they have have similar failure rates. There is however important to distinguish between downtime and failure rates. The Switch (2014) states that the downtime might not be as severe for failures on one of the modules in the full-power converter, as they can still operate on partial power.

Arabian-Hoseynabadi et al. (2009) find that the total availability is higher for the DFIG for smaller wind turbines, but for the larger wind turbines the availability is highest for the PM generator. They do however conclude, in the same matter as Carroll & Mcdonald (2013) and Fischer et al. (2015), that more data needs to be available and processed to conclude upon a preferred turbine technology regarding reliability. For larger wind turbine, reliability data are scarce, and there are indications that these have higher failure rates than the smaller (Spinato et al. 2009). Most reliability studies are based on data from well-known, smaller, onshore wind turbines, and the data might not be applicable for larger turbines. Especially the complexity of the large gearboxes might lead to lower availability, as indicated by Arabian-

Hoseynabadi et al. (2009) and Carroll & Mcdonald (2013). One point is that the multi-megawatt wind turbine technology is under development, and that reliability generally is lower for less mature technologies. Siemens AG (2011) is focusing on the DD-PMG configuration for their large (multi-megawatt) turbine segment, because of the advantage of eliminating a heavy gearbox and reducing the number of rotating and wear-prone parts. They claim that this gives them the possibility to produce turbines with a more reliable drivetrain (Siemens AG 2013).

2.2 NdFeB magnets

2.2.1 Overview

The NdFeB magnets were first developed in the 1980s (Sheridan et al. 2014; Du & Graedel 2011a). It outperformed the then-strongest samarium-cobalt magnets. With the samarium content, these magnets were the first permanent magnets containing rare earth elements. The NdFeB magnets are about 2.5 stronger then the samarium-cobalt magnets. They have the alloying element of iron, which is cheaper and more abundant than cobalt (BGS 2011).

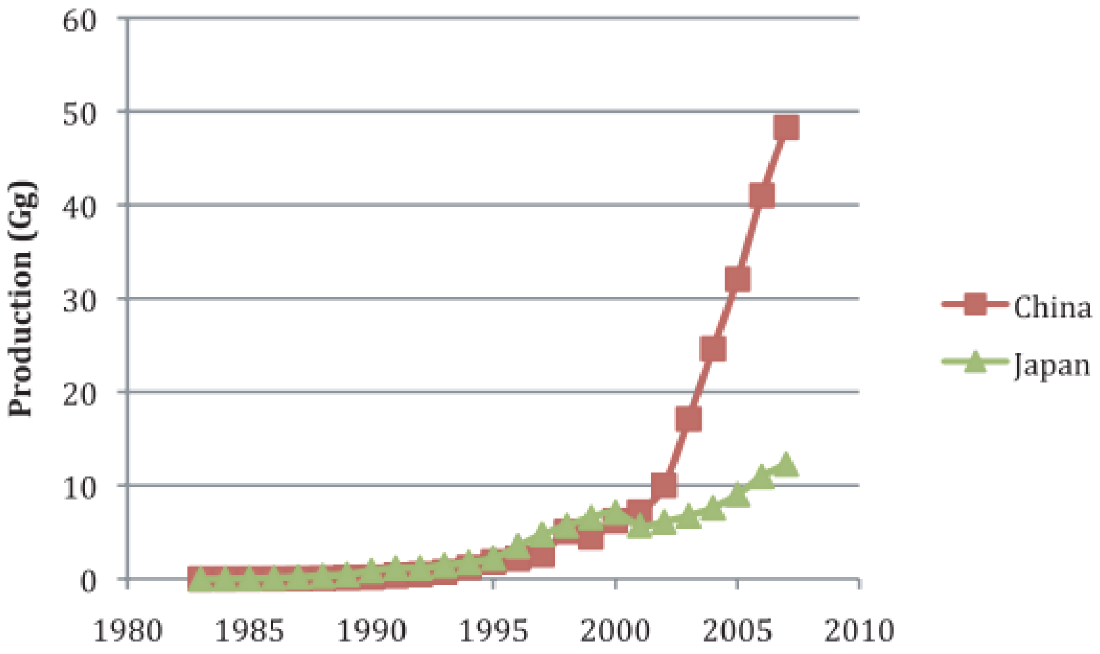

Figure 2-7, Historical NdFeB magnet production in China and Japan in gigagrams from 1983-2007 from 1983-2007. Source: Du & Graedel (2011a)

Both bonded and sintered magnets exist. Bonded magnets were developed by General Motors in the US, and are produced by melt spinning the NdFeB alloy with a polymer-bonding (Brown et al. 2014). The bonded magnets are magnetically weaker, but are more corrosion resistant than their sintered counterparts. Sintered magnets were developed by Hitachi in Japan. 90% of the NdFeB magnet market are sintered magnets (Brown et al. 2014).The production of sintered magnets is explained in section 2.2.3.

From figure 2-7, we see an increase in the volume of the magnet production in China and Japan since 1985. After year 2000, there has been a rapid increase in Chinese NdFeB magnet production. From figure 2-8, we see that China and Japan always have had the largest shares of the magnet production. We see that China now has overtaken the market leading position from Japan.

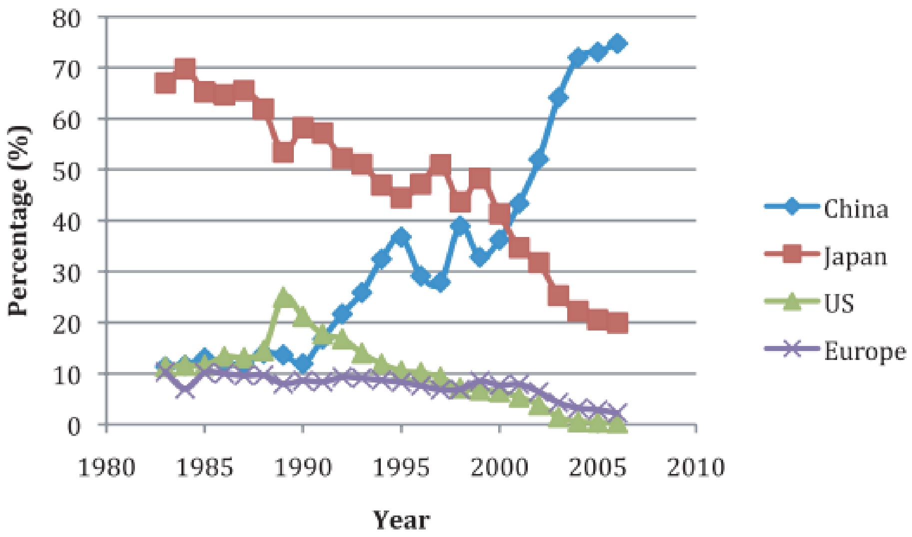

Figure 2-8, Percentage of historical NdFeB magnet production by region from 1983-2007. Source: Du & Graedel (2011a)

2.2.2 The use of REEs in NdFeB magnets

Of the total REE on the market, 20% is used in permanent magnet production (Schüler et al. 2011).

The magnets contain about 65-70% iron (Fe) (Schüler et al. 2011). 1% is Boron (B). The rest of the content is RE metal. The rare earth metals are preferred due to their excellent magnetic properties. Most of the RE metal used in NdFeB magnets is neodymium (Nd). Sprecher et al. (2014) emphasise that in practice, the main REE agent is an alloyed element of neodymium and praseodymium (Pr). This is supported by several sources (Du & Graedel 2011a; Bauer et al. 2011; Schüler et al. 2011). The rare earth element praseodymium is one atomic number lower than neodymium. The two elements have very similar properties. Their similarity makes them difficult and energy consuming to separate, so according to Du & Graedel (2011a) and Bauer et. al (2010) they will be alloyed in the same ratio as they are found in the ores. Thus, the neodymium content is normally about 4 times higher than the praseodymium content. Combining the two elements does not change the properties of the magnets significantly; it can rather increase the field strength when dysprosium (Dy) is an additive in the magnet (Bauer et al. 2010).

The rare earth element dysprosium (Dy) is added to the NdFeB magnets to improve the magnetic performance during higher temperatures. It also reduce the corrosiveness of the magnets (Hoenderdaal et al. 2013). Hence, the use of dysprosium can be a benefit for permanent magnets in wind turbine applications. The Dy content is typically 3-5% of the total weight of the magnet. Terbium can also be used to obtain similar properties of the permanent magnet. The terbium content will typically be 1% or less of the total weight (Du & Graedel 2011a). Innovation is high within the field, and there are reports that Dy also can be substituted by yttrium (Y) (Elshkaki & Graedel 2014) or holmium (Sprecher et al. 2014). The previous CTO of Siemens Wind Power, Henrik Stiesdal, has stated that they would be able to eliminate the dysprosium (and other truly rare REEs) from their turbines "…in a few years time" (Brush 2014; CWIEME Berlin 2014). REEs will be covered in detail in section 2.3.

2.2.3 Production of sintered magnets

Sprecher et al. (2014) present a detailed description of the NdFeB magnet processing route. A brief description will be given in this section.

Strip casting is used for the alloying of the neodymium, iron and boron elements. The mixture of the metals is molten in an induction furnace, and is poured over a fast spinning copper wheel to solidify the alloy into thin flakes. The rapid solidification prevent free iron of forming in between the alloy crystalline structure, thus avoiding a weakening of the magnetic properties of the alloy.

During hydrogen decrepitation, the flakes are treated with hydrogen. A chemical reaction in the grain boundary of the crystalline structure make the flakes collapse into fine powder. This reduces the energy needed during jet milling. In this next jet milling stage, the powder is milled to a particle size 5-7 µm.

Then the fine particles need to be pressed before sintering. First, to make the finished magnets resistant against demagnetization, a magnetic pulse finely aligns the NdFeB particles. The particles now have a magnetic axis. Then, die setting or isostatic pressing is used to press the aligned particles.

Next, the compressed NdFeB is vacuum sintered at a pressure of 2-10 mbar and temperature around 100 °C. A solid magnet mass is now formed without liquefaction, thus preserving the aligned crystalline structure.

The magnets are now grinded and sliced into their final shape. The material losses during this process will depend on the complexity of the desired shape. Magnets used in smaller applications like hard disk drives will have higher losses than magnets used in wind turbines. Sprecher et al. (2014) assume the grinding losses to be 15-20% in Europe and 40% in China for hard disk drive applications. The lost material can be recovered and re-processed.

NdFeB magnets does corrode in humid air and acid environments, and this is one of the main restrictions of the use of permanent magnets (Drak & Dobrzański 2007). The corrosion resistance depends on the specific production technology of the NdFeB magnets. Additives are often used to increase the corrosion resistance. Sintered magnets are in general very corrosive, and some protection is often applied during production. Protective metallic coatings are most often used. The metals used are nickel, chromium, aluminium, zinc, tin, silver and gold. Multi-component coatings like nickel-chromium or nickel-copper may also be used. Organic polymer coatings can be beneficial in low temperature applications. Chen et al. (2014) report that nickel, zinc and nickel-copper coatings are most often used in industry. Sprecher et al. (2014) assume that a nickel coating is applied by electroplating for magnets used in hard disk drive application. For rougher environments, Sprecher et al. (2014) suggest welding the magnet into a stainless steel canister as protection.

Before use, the magnets must be magnetised. This is performed by subjecting the magnets to a strong magnetic pulse (4-8 T) (Sprecher et al. 2014).

2.3 Rare Earth Elements

2.3.1 Introduction

Due to their chemically similar properties, a group of 17 elements are grouped together and called rare earth elements (REE). The main part of the group is the lanthanides, the 15 elements with atomic numbers from 57 to 71. Scandium (atomic number 21) and yttrium (atomic number 39) make up the two remaining elements in the group (BGS 2011; IAEA 2011).

The REEs are not as rare as their name implies, with a total abundance in the earth's crust of 220 ppm. This exceeds e.g. carbon (200 ppm). Most of the elements has an abundance exceeding other well-known metals like cobalt, lead and tin. All REEs are more abundant than mercury or silver (Gupta & Krishnamurthy 2005b). These more known metals are however often found in higher concentrations than the REEs. This means that there are few deposits with a high enough degree of REE to be of economic value. The complexity of extracting the REEs from the ores also makes them *rare* on the world market of metal, at least in a historical perspective.

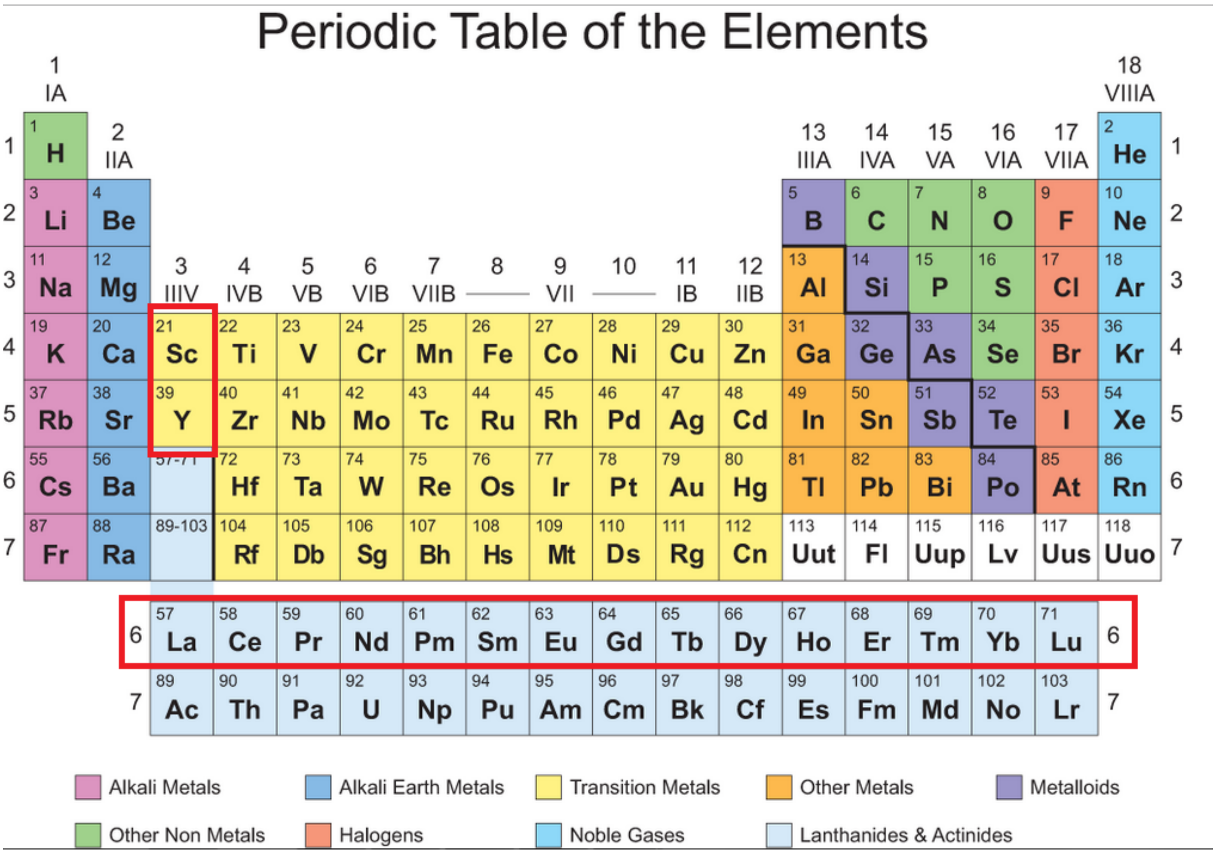

Figure 2-9, Periodic table of the elements with the REEs highlighted. Source: lgoscience.com (n.d.)

The similar chemical and physical properties of REEs make them hard to separate from each other, and is the reason why some of the REEs was unknown until the 20th century (BGS 2011). They are usually subdivided into light REEs (LREEs) and heavy REEs (HREEs). The LREE group consists of the elements with atomic numbers from 57 to 63. In rising order with respect to atomic numbers, these elements are lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm) and europium (Eu). The HREE group has the higher atomic numbers from 64 to 71. The elements in the group are gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium

(Yb) and lutetium (Lu). Yttrium (Y) is also classified as a HREE. Scandium (Sc) is more similar to the LREEs and is often classified in this group. The HREE group is the less abundant, and is only produced in larger quantities is some deposits. Smaller quantities can be produced as byproducts after energy-intensive processing in larger LREE mines (Elshkaki & Graedel 2014; Koltun & Tharumarajah 2014). The rate of production is therefore much lower than for the LREEs (Gupta & Krishnamurthy 2005b; BGS 2011; IAEA 2011).

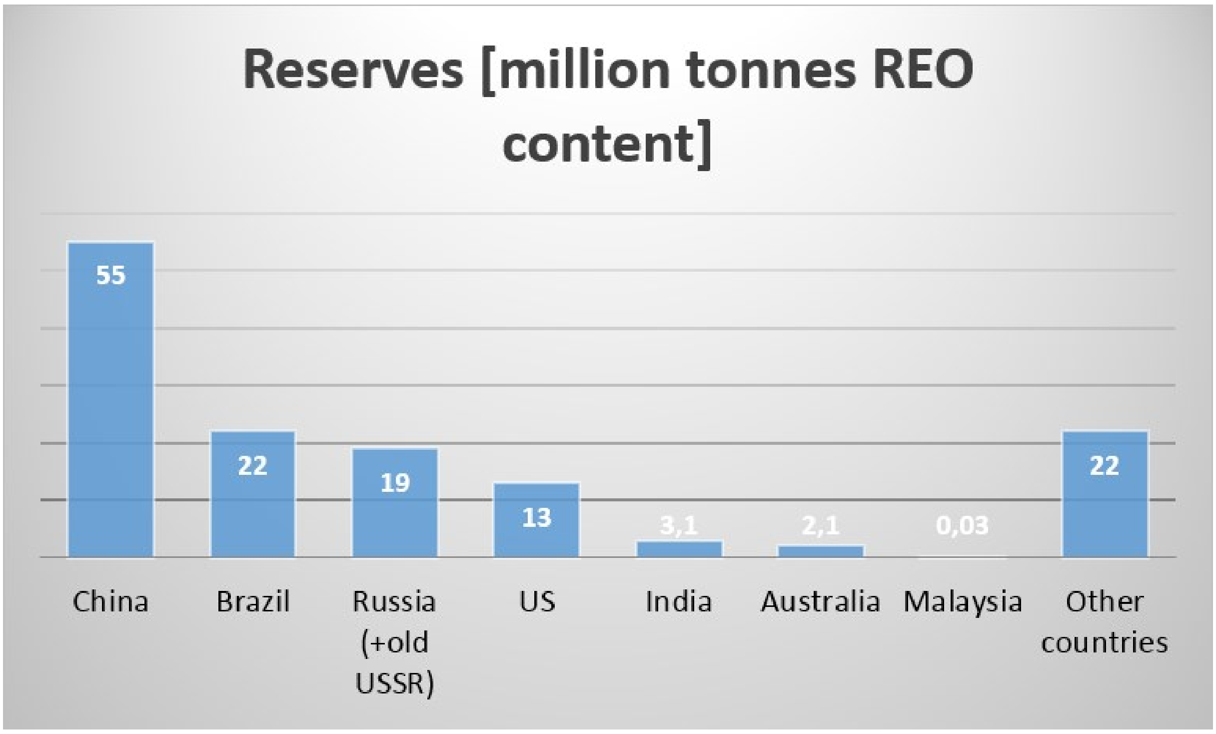

Figure 2-10, Global reserves of REE. Sources: Humphries (2013; US Geological Survey (2014)

From figure 2-10, we see that China has the largest reserves of REEs. From table 2-1, we see that China even more dominates the global REE production. The monopolistic situation of the market is one important reason for the rising attention of the REE in research and at governmental level (Navarro & Zhao 2014; Habib & Wenzel 2014).

Table 2-1, Global REO production by country in 2013. The table is compiled from data from US Geological Survey (2014)

COUNTRY	MINED REO CONTENT [TONNES REO CONTENT]	RELATIVE SHARE OF GLOBAL PRODUCTION
CHINA	100000	89,48%
US	4000	3,58%
INDIA	2900	2,59%
RUSSIA	2400	2,15%
AUSTRALIA	2000	1,79%
VIETNAM	220	0,20%
BRAZIL	140	0,13%
MALAYSIA	100	0,09%

2.3.2 Type of minerals and deposits

Nearly 200 minerals contain more than 0,01% rare earths (Gupta & Krishnamurthy 2005b) . The RE elements are however mainly found in economical feasible amounts in only three minerals: bastnäsite, monazite and xenotime. In addition, a unique type of ion-adsorption clays found in Southern China contains REEs that are feasible for extraction.

2.3.2.1 Bastnäsite

Bastnäsite (*RE(CO₃)F*) is a fluorcarbonate mineral, and contains around 70% REO. Around 98% of the REOs are as LREEs (mostly cerium, lanthanum, neodymium and praseodymium). It has lower radioactivity than the other REO containing minerals. The weak radioactive thorium content is between 0-0,3 %. Uranium content is around 0,09% (Jordens et al. 2013). In 2011 almost 50% of the produced REO was of bastnäsite origin. In the largest REO mine in the world, the Bayan Obo mine in Inner Mongolia, China, 75% of the REO content occurs in bastnäsite.

2.3.2.2 Monazite

Monazite (REPO4) is, after bastnäsite, the second most frequent REO-containing mineral found. It is a phosphate mineral. Great commercial ores are found in sand or placer deposits (Talens Peiró & Villalba Méndez 2013). It is also found as hard rock in igneous and metamorphic rocks and certain vein deposits. It also occurs in veins together with bastnäsite in the Bayan Obo ore. 25% of the total REO content in the Bayan Obo is monazite (Ren et al. 2000). Similar to bastnäsite, most of the deposits contains 70% REO, where around 83-95% of the content is LREEs. Some deposits are reported to have lower REO content, as low as 35%. The slightly higher degree of the valuable HREE in monazite compared to bastnäsite is a commercial benefit. However, the higher degree of thorium (4-12%) make the processing of mineral more complex, as most countries have regulation for the handling of the radioactive content (Jordens et al. 2013). Some deposits also contain uranium. Typically, the uranium content is low, but some deposits contain 14%. This could however be a benefit, as the high uranium content could be a valuable byproduct in production. (Gupta & Krishnamurthy 2005b; Schüler et al. 2011)

2.3.2.3 Xenotime

Xenotime (REPO4) is another phosphate mineral. It has a typical REO content of 67% (Gupta & Krishnamurthy 2005b). It contains more of the valuable HREE than monazite. 63% of the total REO content is the heavy RE element yttrium. The LREE content is only 8-9% of the total REO.

It is the scarcest of the three minerals. It can be a small constituent in gneiss and granite, but is mostly found in placer and sand deposits. Here, it is typically found alongside monazite. Usually, the xenotime content is only 0,5-5% of the monazite. It also occurs in small amounts in cassiterite (tin) placer deposits and other heavy mineral sand deposits (Talens Peiró & Villalba Méndez 2013). REE will be processed as minor byproducts from these deposits.

2.3.2.4 Ion-adsorption clays

These are the only REE deposits to occur in a non-solid state. A complex geological process, because of the climatic conditions in Southern China, led to their formation. After weathering of primary REE-containing granite, REEs dissolved from the mother rock in a trivalent ion form into solutions of RE and was subsequently adsorbed onto clays (Yang et al. 2013).

Under humus top soil layer (0,3-1 m deep), there is a main ore body as a regolith layer. The main ore body is 5-30 m deep (Yang et al. 2013). The REO content of the body is only about

0,03-0,15%. Considering the low REO content, the profits of the mines are high. This is because the ore is much easier to process than other types of REE deposits.

The clays are also high valued because of their high content of the scarce REEs. The composition varies greatly from deposit to deposit (Gupta & Krishnamurthy 2005b). Typically, they have an unusual high content of yttrium (60%) and other HREEs. The great variation between deposits, together with typical values from other type of mineral deposits, is shown in table 2-2 below.

Table 2-2, Table of the ore composition for some selected ores. Source: Gupta & Krishnamurthy (2005b)

	Bastäsite		Monazite	Xenotime	Ion-adsorption clays	
	Mountain Pass, USA	Bayan Obo, China	Mount Weld, Australia	Malaysia	Longan, China	Xunwu, China
La	33,20 %	23,00 %	26,00 %	0,50 %	1,82 %	43,40 %
Ce	49,10 %	50,00 %	51,00 %	5,00 %	0,40 %	2,40 %
Pr	4,34 %	6,20 %	4,00 %	0,70 %	0,70 %	9,00 %
Nd	12,00 %	18,50 %	15,00 %	2,20 %	3,00 %	31,70 %
Sm	0,78 %	0,80 %	1,80 %	1,90 %	2,80 %	3,90 %
Eu	0,12 %	0,20 %	0,40 %	0,20 %	0,10 %	0,50 %
Gd	0,17 %	0,70 %	1,00 %	4,00 %	6,90 %	3,00 %
Tb	0,02 %	0,10 %	0,10 %	1,00 %	1,30 %	-
Dy	0,03 %	0,10 %	0,20 %	8,70 %	6,70 %	-
Ho	0,01 %	-	0,10 %	2,10 %	1,60 %	-
Er	0,00 %	-	0,20 %	5,40 %	4,90 %	-
Tm	0,00 %	-	-	0,90 %	0,70 %	-
Yb	0,00 %	-	0,10 %	6,20 %	2,50 %	0,30 %
Lu	0,00 %	-	-	0,40 %	0,40 %	0,10 %
Y	0,09 %	0,50 %	-	60,80 %	65,00 %	8,00 %

2.3.3 Common production practices

I will go through typical production practices for REEs. In the literature, the terms used for the production processes are different. Especially the terms *extraction* and *separation* seem to be used interchangeably for several of the processes. I will use the same terms as Talens Peiró & Villalba Méndez (2013) use in their article.

More elaboration will be given the bastnäsite production in Bayan Obo in section 2.3.4, since it is the investigated production scheme in this assessment. Production practices and certain environmental concerns of ion adsorption clays is different from the classical production from mineral deposits. This will not be treated in this chapter of the thesis, but the interested reader can find this information about the ion-adsorption clay in appendix A.1.

2.3.3.1 Mining

The mining does not differ substantially between the three most common minerals (bastnäsite, monazite and xenotime). The exact operation is dependent on the mine site in question. The great majority of the mines are surface mines that use standard open pit operations (Talens Peiró & Villalba Méndez 2013). Standard procedure is drilling and blasting the crude ore in a hard rock deposit. It is then loaded onto haul trucks or railway cars and transported to a milling plant.

When REEs are produced as byproducts from placer or other sand deposits, there normally is no need for blasting the ore. The mining operations are standard, and they do not change significantly relative to the REE content (Gupta & Krishnamurthy 2005a).

2.3.3.2 Beneficiation

In beneficiation, the ore is separated into valuable mineral concentration(s) and non-valuable gangue. The ore is first finely milled, often to diametrical sizes less than 100 μm. The second step is often a physical beneficiation of the ore. This is to achieve a first division of the valuable element(s) and the non-valuable elements into rough bulk concentrates. This performed in different ways.

For the non-hard rock ores, the sand and placer deposits containing monazite and xenotime, separation by gravity can be a good way to achieve a first rough division. If this is performed, wet or dry shaking tables are often used. The beneficiation scheme chosen depends on the deposit mineralogy. In addition cyclones and spirals can be used for rougher particle separation. These types of sands have several by-products, and the magnetic minerals can be beneficiated by magnetic separation. There can also be small differences in the surface conductivity of the minerals, and this is utilized during high tension electrostatic separation of the mineral particles. For example, in the Indian deposits containing ilmenite, monazite and xenotime, monazite can be separated by the two others by a magnetic separation. Afterwards, xenotime and ilmenite can be separated by electrostatic separation, due to the low conductivity of xenotime. From this scheme, we understand the nature behind the complex process schemes found for these type of ores, and that different methods are used in different combinations for a deposit to separate the minerals. The scheme is naturally dependent of the characteristics of the deposit (Gupta & Krishnamurthy 2005a).

Chemicals are often used to enhance the beneficiation process. This is often applied after some sort of physical sorting. For bastnäsite and the hard rock mined monazite ores, beneficiation with chemicals is needed to part the minerals of the ore. In Bayan Obo, where magnetic iron minerals like hematite and magnetite appears with the bastnäsite and monazite, physical beneficiation techniques, like magnetic separation, play an important part ahead of and after a beneficiation with chemicals. (Gupta & Krishnamurthy 2005a)

In the relevant literature, they describe flotation techniques to separate and enhance the mineral concentrates (Gupta & Krishnamurthy 2005a; Talens Peiró & Villalba Méndez 2013; Schüler et al. 2011). In froth flotation, chemicals are added to a wet mineral feed. The depressant chemicals make some of the gangue minerals to settle at the bottom of the flotation cells. The collector chemicals separate the desired, valuable minerals, and the air bubbles produced in the flotation cells transports these minerals to the surface of the cell. A froth layer is formed on the surface. The froth is removed, and after a cleaning process becomes the mineral concentrate that is the product of the beneficiation stage. The concentration of REO in the concentrates is normally around 60-70%. It can be as high as 90%. Often secondary concentrates, with a lower concentration than the primary, is also prepared.

2.3.3.3 Extraction of beneficiated concentrate

The boundaries between the beneficiation step and the separation step is unclear. I have chosen to call the stage of further chemical treatment of the mineral concentrates for an extraction stage. It is this term Talens Peiró & Villalba Méndez (2013) use, although they do treat this as a sub stage of the beneficiation. Schüler et al. (2011) call the stage as "decomposition of RE concentrate". Here, the term "extraction stage" will be used about this part of the processing chain.

During this process, there is a distinction between bastnäsite concentrates and the monazite and xenotime concentrates. The first mineral is a carbonate-fluoride mineral ($RECO_3F$). The latter group are phosphate minerals ($REPO_4$).

There are several ways to extract the bastnäsite concentrate. The majority has RE chlorides as the product of this process. The aim of the stage is, in addition to removing impurities, to get the REEs in a soluble form.

Some methods require roasting with a chemical in a kiln at elevated temperatures to break the bastnäsite fluorcarbonate matrix. In Bayan Obo for example, the chemical used is sulphuric acid. The RE product of this process is RE sulphate. This needs to be further treated chemically in 1-3 steps to obtain RE chlorides and remove additional impurities. This usually involves using hydrochloric acid.

A direct chlorination method (with Cl_2) has been applied in both China and the US. It is in a furnace at elevated temperatures (over 1000 °C) that the bastnäsite is turned into RE chlorides ($RECl_3$) with CO_2 and O_2 as flue gases and RE fluorides (REF_3) as a byproduct. The fluorides are further treated by the Kreusi and Duker method, consequently more REE is recovered as RE chlorides. This method consists of a digestion with caustic soda and neutralisation with hydrochloric acid. A modified version of this direct chlorination step can be used for treating the xenotime and monazite concentrates (Gupta & Krishnamurthy 2005a).

A strong digestion with hydrochloric acid can replace the first direct chlorination step. The Mountain Pass bastnäsite concentrate can be treated this way. The temperature for this step is lower (93 °C) than for the direct chlorination step. Next, the products are treated by the same Kreusi and Duker method.

No new literature was found for the extraction of monazite. Talens Peiró & Villalba Méndez (2013) suggest the alkali treatment of Rhône-Poulenc developed in the 1950s. Gupta & Krishnamurthy (2005a) report of one acid method to treat xenotime.

This extraction stage is very thoroughly treated in the article published by Talens Peiró & Villalba Méndez (2013). They report the energy use for the methods to be very different. The lowest is the Kruesi and Duker method used in Mountain Pass, US with 0,03-0,04 MJ/kg REM. The bastnäsite in China and the direct chlorination techniques is reported to have a demand of 6,09-9,29 MJ/kg REM.

2.3.3.4 Separation

Due to the similarity of the properties of the REEs, this is one of the most complex processing stages. After the extraction stage, we have a soluble product. During the separation stage, the product from the extraction is dissolved in a solvent medium. Then, several techniques are used to separate the one type of RE ions from other RE ions.

Selective oxidation and selective reduction are separation methods used for efficiently separating some REEs (BGS 2011; IAEA 2011; Gupta & Krishnamurthy 2005a). The techniques used today are mainly ion exchange or solvent extraction. In these techniques, the small difference in basicity between the elements is used to separate them.

Solvent extraction is the separation process used in most commercial application. It is also called liquid-liquid extraction, since an interaction between two liquid phases separates the individual elements (BGS 2011). The first phase is an aqueous phase, originally containing the solution with RE ions. The second phase is an organic phase, containing organic extractants dissolved in an organic solvent. The phases are immiscible. The solvent make the organic phase more inviscid, ensuring good contact with the aqueous phase (Gupta & Krishnamurthy 2005a). The extractants collect the RE ions into the organic phase by forming complexes with them. All elements have a specific distribution coefficient. This is the ratio between their concentrations in each of the phases in equilibrium. Dependent on their basicity, all elements will have different concentrations in the organic phase. Some elements will have higher concentrations in the organic phase than the other elements. Now, the organic phase is taken to a stripping stage, where the elements are stripped back to the aqueous phase. This operation is as one solvent extraction stage. By performing this multiple times, the concentrations of some selected REEs will be enhanced. Tens to hundreds of stages is necessary, and is dependent on the desired purity wanted for the element in question. Gupta & Krishnamurthy (2005a), IAEA (2011) Talens Peiró & Villalba Méndez (2013) describe this stage in more detail.

Ion exchange is also a technique used commercially today (BGS 2011, Talens Peiró & Villalba Méndez 2013). Fractional crystallisation and fractional precipitation was techniques previously used (Gupta & Krishnamurthy 2005a; Talens Peiró & Villalba Méndez 2013). Today most of the commercial production use solvent extraction. Solvent extraction is used in for the production in Bayan Obo, Mountain Pass and of processing of the Mount Weld ore in Malaysia (Schüler et al. 2011; Lee Bell 2012).

2.3.3.5 Refining

The individual RE oxides can be refined to produce very pure individual RE metals. There are different reports about how this is performed. Most of the REEs are normally refined in a molten salt electrolysis (Schüler et al. 2011; Sprecher et al. 2014; Talens Peiró & Villalba Méndez 2013; Zhang et al. 2004). In the molten salt electrolysis, the electrolyte is a solution of the product from the separation. Little detailed documentation is found about how this electrolysis is performed for the REEs, but some can be found in IAEA (2011).

The relevant literature briefly mentions other refining methods. Schüler et al. (2011) report the HREEs reduced by a type of metallothermic reduction with argon in hot container in vacuum. Talens Peiró & Villalba Méndez (2013) refer to a metallothermic reduction using a reducing agent of hydrogen or carbon or metals like lithium, sodium, potassium, magnesium, calcium or aluminium, but in a similar fashion as Schüler et al (2011). Koltun & Tharumarajah (2014) report the HREEs to be produced by electrolysis with a aqueous solution or pyrometallurgy. IAEA (2011) also briefly present three different ways of reduction, namely oxide reduction (for Sm, Eu and Yb), halide reduction (for the other REEs) and a metallothermic reduction with zinc in molten salt (for Nd only).

Individual metals with over 99% purity are often produced. The molten salt electrolysis requires more energy input than the metallothermic reduction. In the research of Talens Peiró & Villalba Méndez (2013) the electrolysis is estimated to be 100 times more electricity consuming than the metallothermic reduction (per kg REM produced).

2.3.4 Production of REEs in the Bayan Obo mine and Baotou processing plant

The Bayan Obo mining district is in the Inner Mongolia Autonomous region in China. The mine itself is one of the largest discovered ore resource in the world (Schüler et al. 2011). It contains iron, niobium and rare earths. The primary production is iron, with estimated reserves being 1500 Mt. The REE reserves are also large, 48 Mt (Wu 2008). The production of REEs started in 1959. Much of the REE content of the ore was wasted, due to the low recovery rates. For the first decades of production this was around 10%. Now the recovery rate is around 50% (Schüler et al. 2011).

Both bastnäsite and monazite minerals are found in the ore. About of 25% of the REEs in the Bayan Obo mine occur in monazite, 75% is bastnäsite.

The RE processing plant is in the city of Baotou, approximately 130 km from Bayan Obo. It is the largest industrial city in the Inner Mongolia Region and often called “The rare earth capital of the world”. This is because of the importance of the RE production to the world market, around 54% of total REE production was from Bayan Obo in 2007 (Du & Graedel 2011b).

2.3.4.1 Details about bastnäsite production scheme of the Bayan Obo Ore

Presented here are some details of the production of neodymium metal from the bastnäsite concentrate in the Bayan Obo ore.

Mining

First, the ore is mined at 3 large ore sites in the Bayan Obo Mining District. The total amount of mined ore is over 13 million tonnes per year (Qifan 2011). The mines are open pit mines, using a standard open pit mining approach (BGS 2011). After removing the overburden (surface) material, the rock is drilled and blasted, and the ore is loaded to trucks and hauled to the milling plant situated in Bayan Obo (Gupta & Krishnamurthy 2005a; BGS 2011). Large amounts of waste rock needs to be stockpiled, and is later backfilled. Potential contamination by heavy metals, sulphides or thorium into rainwater is a potential hazard in the open pits and the stockpiles (Schüler et al. 2011). The open mining operations are dusty.

Beneficiation

At the milling plant, the valuable parts of the ore are extracted into concentrates. Gupta & Krishnamurthy (2005a) describe the beneficiation process of the Bayan Obo ore. First, the ore is finely grinded. A 70% iron concentrate is prepared by magnetic separation and a bulk flotation of the grinded ore. According to Krishnamurthy, Na2CO3, NaSiO3 and paraffin soap are the important chemical inputs in the flotation process. After the flotation, an iron and niobium concentrate is produced on top of the cell.

The tailings are valuable REEs, and are sent to further processing. There are produced three concentrates (IAEA 2011). The bastnäsite concentrate is the largest fraction, containing 57 % of the total REO recovered (Ren et al. 2000). There is a monazite concentrate produced as well, but the fraction is only around 12%. The remainder of the REOs is in a mixed concentrate of both bastnäsite and monazite. This concentrate is then a fraction of around 31% of the total weight of REOs.

Extraction

The three main processes in the extraction stage is acid roasting by sulphuric acid, leaching and digestion and dissolution. The digestion is in a sodium hydroxide solution, and subsequently dissolved by hydrochloric acid. The main chemical reactions are listed in figure 2-11. The chemical treatment of the bastnäsite concentrate result in RE chlorides. These are suitable for separation into individual RE metals in the solvent extraction process. Detailed information about the extraction processing scheme can be found in the work by Talens Peiró & Villalba Méndez (2013).

Acid roasting

$$2RECO_3F + 3H_2SO_4 \rightarrow RE_2(SO_4)_3 + 2HF + 2H_2CO_3$$

Leaching

$$4/3RE_2(SO_4)_3 + 12H_2O + 2NaCl \rightarrow RE_2(SO_4)_3 \cdot Na_2SO_4 \cdot 12H_2O + 2/3RECl_3$$

Digestion and dissolution

$$RE_2(SO_4)_3 \cdot Na_2SO_4 \cdot 12H_2O + 6NaOH \rightarrow 2RE(OH)_3 + 4Na_2SO_4 + 12H_2O$$

$$RE(OH)_3 + 3HCl \rightarrow RECl_3 + 3H_2O$$

Figure 2-11, Important chemical reactions during the extraction of the Bayan Obo ore. Source: Talens Peiró & Villalba Méndez (2013)

Solvent extraction

In Bayan Obo the RE elements are separated by solvent extraction (Schüler et al. 2011). The feed of RE chlorides are as ions in an aqueous phase (Bouorakima 2011; Talens Peiró & Villalba Méndez 2013).

The organic solvent is dissolved in an HCl medium to ensure good contact with the feed of RE ions. The organic solvent forms complexes with these RE ions. Consequently, the RE elements enter the (second) organic phase. The extract containing the complexes is scrubbed for impurities. The organic complexes in the extract are separated during gravity settling in the Baotou processing plant. We have now separated the RE elements. The RE elements leave the organic phase during a stripping process and re-enter the chloride form. The stripped solvents are recycled at 90% efficiency. There is a need for several stages to separate a maximum of the RE elements. (IAEA 2011; Gupta & Krishnamurthy 2005a)

Reduction

During the reduction stage the neodymium (Pr) oxides are reduced to finally achieve 1 kg of neodymium (Pr) metal. In the Baotou processing plant, reports say that this reduction is performed by molten salt electrolysis (Schüler et al. 2011; Sprecher et al. 2014). There is little information available on how this electrolysis is done for the reduction of rare earth metals. Sprecher et al. (2014) states that the molten salt electrolysis is similar to that of aluminium, known as the Hall-Héroult process.

2.3.5 Environmental concern

2.3.5.1 Radioactivity

The concern that most often reach the public is regarding the radioactive content in some of the deposits. IAEA (2011) and Lee Bell (2012) goes into details regarding this concern. The major concern is the radioactive content from xenotime and monazite ores (Koltun & Tharumarajah 2014). Thorium is the main radioactive element, and the content in monazite is commonly from 4%-12% (Gupta & Krishnamurthy 2005b). Bastnäsite has a lower thorium level, with the Mountain Pass bastnäsite containing 0,2% and 0,002% uranium. The combined iron-niobium-monazite-bastnäsite ore in Bayan Obo contains 0,04% thorium. Xenotime placer deposits in Malaysia contain 2% uranium and 0,7% thorium. Uranium often appears as a fraction related to thorium content.

For the hard rock deposits, the radioactive content is a concern already during the mining stages. Dusty operations pose a danger to the health of workers, especially the long-term exposure to radioactive dust, even if the ionising radiation of regular thorium isotopes like Th-232 is considerably small. The dangers is mostly related to inhalation of these radionuclides, which can harm the lung tissue and cause cancer in the long run (IAEA 2011; Lee Bell 2012).

For mining of sands, the risk of exposure is lower, due to less dusty operations. These sands also have a low concentration of monazite or xenotime and therefore have a lower thorium and uranium content.

One important point is that the radioactive content is an integral part of the mineral itself. In most cases, it is during the processing of the mineral that the REE and thorium content separates. This means that there is a potential for handling most of the radioactive content. However, there will be thorium in the tailings and other waste from all processing steps (Schüler et al. 2011). The lack of handling or poor handling of these tailings is important to avoid contamination of nearby water resources, soil or vegetation by dangerous radionuclides. Poor handling of the radioactive material is the main criticism against the industry from environmentalist, as well as researchers.

2.3.5.2 Other environmental concerns and treatment strategies

From the previous section, it is clear that a proper handling of the tailings is important. This is not only due to the radioactive content, but also due to large concentrations of heavy metals in the tailings. The largest amounts of tailings are created at the beneficiation and extraction stages (Koltun & Tharumarajah 2014). The now up-to-date Chinese regulations require all REE processing to implement complete treatment facilities for the solid waste and the wastewater. This means that the tailings, along with the chemical process waste, need to be properly treated. The large amounts of acids and bases consumed in the separation stage cause environmental concerns, which leads to a huge wastewater emissions with salts (Liao et al. 2013). Now, 85% of all ore dressing wastewater should be recycled according to the new regulations of the Chinese Ministry of Environmental Protection (Schüler et al. 2011; MEP 2011).

The use of ammonium during several stages of production is a concern. Especially during the separation process of solvent extraction, wastewater that contains ammonia is produced. Discharging this directly to the environment will contaminate water resources. Estimates show that between 3000-5000 mg of ammonium was discharged per litre of wastewater. This is 200 times as much as the new Chinese emission limit (Schüler et al. 2011).

Air emissions are most lightly to occur from kilns or furnaces during the extraction stage. HF and other fluoride gases will most lightly be a part of this flue gas together with CO_2 when during bastnäsite extraction. This is because of the fluoride content of the mineral. The use of sulphuric acid can lead to SO_2 or SO_3 emissions (IAEA 2011). Regulations in all RE processing countries require abatement techniques to handle these emissions. CO_2 is a product in one or more processes during the extraction of all minerals. The use of heavy fuel oil and other fuels for the heating processes will emit CO_2, CO, SO_2 and NOx. Fugitive emissions from tailing ponds can also be a problem. In addition to radionuclides, this can be dust containing heavy metals, HF, HCl or CO_2 (Schüler et al. 2011; IAEA 2011).

2.3.5.3 Resource depletion

There is a concern about resource depletion of the REE reserves. Resources are scarce, and there has been some research of the topic. One concern is that the high demand for dysprosium from all deposits may lead to an oversupply of the other REEs, like Nd, La, Ce and Y. (Elshkaki & Graedel 2014; Jordens et al. 2013; Alonso et al. 2012).

The main findings are that there is a concern for the supply of some REEs, especially a few of the HREEs in the short-to-medium future. Recycling, in addition to opening of new mines, will secure that the REEs will not be depleted for several hundred years (Habib & Wenzel 2014). Hoenderdaal et al. (2013) refer to this as a production capacity issue and not an issue of geological scarcity. In addition, new substitution technologies might ease the issue of supply not meeting the demand. (Schüler et al. 2011; Bauer et al. 2010)

2.3.5.4 Examples of specific environmental concerns related to some REE plants

Lynas RE processing plant in Malaysia

Criticism from environmentalists has emerged in most big REE projects. For example, the processing of the (Australian) Mount Weld monazite in the processing plant in Malaysia gained attention. Public opposition postponed the opening of the processing plant for several years. A report from the National Toxics Network stated that: "This proposal [of an operating license for the processing plant] would not be approved in Australia and the Malaysian government should revoke the temporary operating license on this basis"(Lee Bell 2012). The Australian owners were accused of the "not in my backyard"-syndrome, related to the shipping of the "dirty" processing of the ore to Malaysia (Ali 2014).

The tailings from the processing plant contain 500 ppm thorium oxide and 30 ppm uranium oxide. There is no public information about how the detailed management of the thorium content is performed, but the tailings itself end up in an artificial tailing pond. Schüler et al. (2011) report of a strong pond construction with "impervious base and walls", in addition to a groundwater monitoring system on site to satisfy Malaysian regulations. The critics still fear leakages from the pond, as well as a structural failure because of natural disasters, leading to unenviable contamination of the groundwater (Lee Bell 2012).

They also fear that some of the wastewater from the separation stage might contain radioactive elements, along with chemicals and other heavy metals. The wastewater is discharged (after treatment) to a local river. The critics fear a lack of monitoring of this wastewater, and fear a breakdown of the treatment facility. They also fear fugitive air emissions containing heavy metals or radioactive dust from the tailing pond. In 2014, there were still ongoing protests against this processing facility in Malaysia (Boyle 2014).

Bayan Obo and Baotou processing plant

We know that facilities have been improved at the Bayan Obo and Baotou processing plant the later years due to new and stricter environmental regulations. Before now, there has been no treatment of the tailings, and they have been stockpiled in an impoundment. This natural impoundment reached a size of 11 km^2 (Schüler et al. 2011). The pond area has been a dumping site for both the iron and REE processing tailings and reached a total of 150 million tons. There has been no recovery of the thorium content of the ore, so the thorium has been a part of the stockpiled tailings. This fraction is estimated to be around 0,135% of the impoundment or a total of over 2 thousand tons. Since the plant earlier has had a low recovery rate of REEs, the tailings has been so full of minerals and valuable waste that the locals have been able to sell it illegally as valuable concentrates.

The ecological damages are severe due to the lack of treatment (Ali 2014). There are reports of severe loss of vegetation and animal life in the surroundings of the lake, along with human toxicity concerns due to groundwater contamination (Schüler et al. 2011; Bontron 2012). Even though the policies of the Chinese government have changed over the last decade, and a restoration program is in effect, most of the damages in the Baotou area are going to irreversible (Wübbeke 2013). In the REE industry in general, one advantage of increased monitoring is the fact that a more efficient production increases the recovery rates. Consequently, the benefit is economical revenue in addition to improvements of the environmental performance. This has served as an economical motivation for the Chinese government to apply a stricter control of the emissions from the Chinese RE industry.

The Kvanefjeld project on Greenland

Since late 80s, there have been discussions regarding the extraction of uranium and RE from this deposit on Greenland. A potential opening of the Kvanefjeld mine will have a major impact on the availability of HREE in the close future (Hoenderdaal et al. 2013). However, half of the uranium produced will be disposed as tailings in a small local freshwater lake called Taseq. This lake is connected by the river systems to the Arctic sea (Marfelt 2013). A report as early as in 1990 stated that the fluorine, heavy metals and radioactive waste dumped here could potentially affect the ecosystems of the connected rivers and the ocean (Schüler et al. 2011). The owners themselves have reported that they have a system to control that the tailings does not leave the lake, but none has seen the details of these plans.

The increasing snow melting and change of topography due to global warming on the Greenlandic west coast also pose a threat of structural failure of any tailing pond facility on site. The mine has been a political controversy on Greenland. The Greenlandic authorities lifted a legal ban on uranium mining in 2013. After the pro-Kvanefjeld parties managed to form government after the election in December 2014, the plans of opening the mine is now moving forward (Zawadzki 2014; Pulk 2014; Dollerup-Shceibel 2014; Greenland Minerals and Energy Limited 2015). As we have seen, the opening of the mine might be a concern for the local environment. Thinking of the global environment concerns however, the HREE content of the mine might help to solve the supply issues of dysprosium to the NdFeB magnet industry (Hoenderdaal et al. 2013).

3 Materials and methods

3.1 Framework and applied methods of life cycle assessment

3.1.1 The basics of LCA

"*Life cycle assessment addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal*"(ISO 14044 2006). In short, life cycle assessment was developed because of a desire to better understand and address the environmental impacts associated with consumption and manufacture of products (and services).

The following section contains a short introduction of LCA. Readers that are not familiar with the technique is encouraged to read background literature, e.g. ISO 14044 (2006), Tillman, A. M., & Baumann (2004), Finnveden et al. (2009), Pennington et al. (2004) or Rebitzer et al. (2004)

There are several ways of performing an LCA. However, all practitioners stick to four main phases. They are in-depth described in the background literature of LCA.

The four phases are:

1. Goal and scope definition

2. Inventory analysis (LCI)

3. Impact assessment (LCIA)

4. Interpretation

The goal and scope definition phase provide a description of the system and a motivation of the study. The methodological choices are made and the practitioner will find the best approach to address the goal of the study, e.g. what type of LCA to perform. Typically, the functional unit and system boundaries are decided in this phase. (ISO 14044 2006; Pennington et al. 2004)

During the inventory analysis, the practitioner will estimate the material flows within the considered system. Consumption of resources, waste flows generated and emissions occurring within the system must be quantified at this stage. The data collection forms the basis for the assessment. Databases are often used to aid the practitioner during the construction. This allows a high number of data entries in the analysis, linking large value chains to the use of resources or materials. (ISO 14044 2006; Pennington et al. 2004)

The impact assessment phase is where the environmental burden from the system is analysed. To find a measure of the environmental burden related to the demand of the functional unit, characterisation factors are established. They relate the environmental stressors found in the inventory to different sets of impact categories decided by the practitioner, i.e. global warming or freshwater eutrophication (Rebitzer et al. 2004; ISO 14044 2006).

Interpretation is continuously performed throughout the whole assessment. The amount of data processed, processes constructed and assumption taken is large, requiring constant reflection. At the end, it is customary to discuss the results and uncertainties of the assessment. (Rebitzer et al. 2004; ISO 14044 2006)

The inventory is constructed as an interdependent linear system. Linear algebra is used for calculating the system properties. The methods are based on the Nobel Prize Winning techniques of Wassily Leontief.

3.1.2 Ecoinvent database

The Ecoinvent database is a comprehensive database used for constructing life cycle inventories. The database contains data on resource extraction, material and energy supply, chemicals, metals, agriculture, waste management services and transport services. It is the world-leading supplier of this type of databases. It includes thousands of inventory datasets. The database is continuously expanding, and the latest release was the V3 in 2013 (Weidema et al. 2013). An overview and methodology of the database can be found in the article of Frischknecht et al. (2007).

3.1.3 ReCiPe

ReCiPe was developed as a framework for LCA practitioners to be able to perform more equivalent impact assessments. The framework aimed to introduce limited number of common indicators for assessing the environmental burdens found. The indicators are based on two approaches: midpoint categories and endpoint categories.

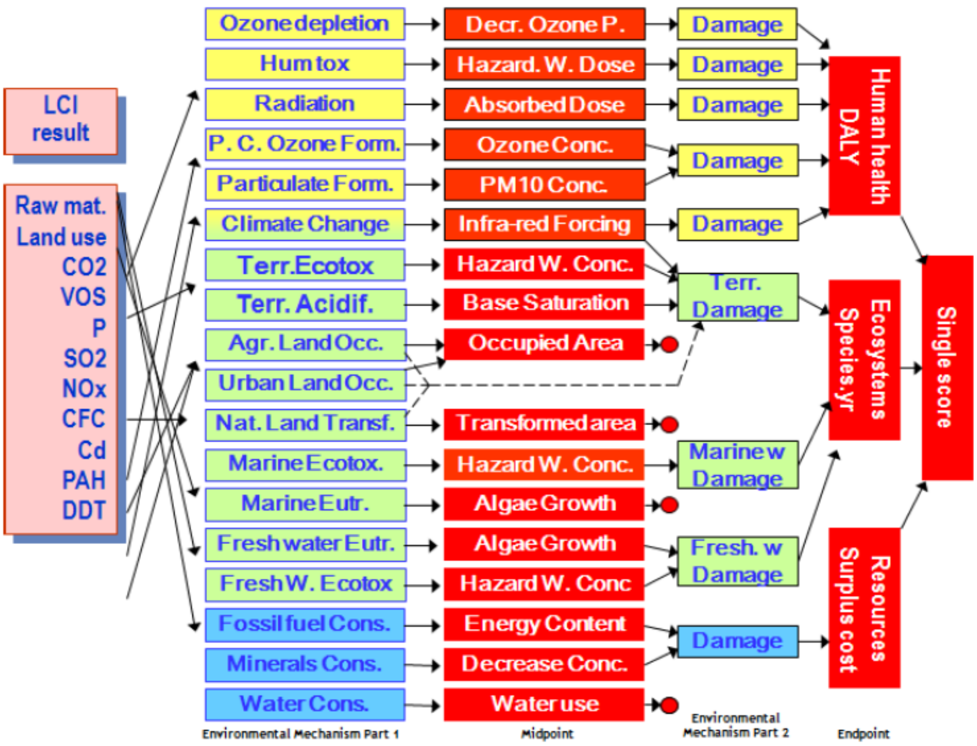

Figure 3-1, Illustration of the approach of the ReCiPe framework, showing the midpoint and endpoint categories. Source: Goedkoop et al. (2009a)

The 18 midpoint categories have a lower uncertainty and a high acceptance within the scientific community. The 3 endpoint categories are more intangible, and a more intricate procedure beyond the midpoint calculations are used to find the endpoint impact. This leads to a higher uncertainty of the results of the endpoint categories. In the effect chain of an environmental impact from the cause of a stressor, the midpoint indicator approach will try to gather the effects in a common physical unit in the midpoint of this chain. The endpoint indicator will estimate the end effect of the environmental impact, e.g. damage to human health. The advantage of the latter is that the units of the endpoint categories are easier to understand for people without knowledge of LCA. The report from Goedkoop et al. (2009a) provide in-depth description of this framework.

3.1.4 Arda

Arda is the name of a NTNU software, developed by the Industrial Ecology Programme at the Norwegian University of Science and Technology (NTNU). The user must make a foreground inventory in a supplied template. The background inventory is constructed in the Ecoinvent Database. The current Arda version 18 uses the Ecoinvent Database version 2.2. It also uses the ReCiPe framework in the LCIA phase to calculate the environmental impacts.

The software also provides a possibility to run structural path analysis (SPA) of the system. A SPA allows us to decompose the impacts for the different pathways (process routes) within the system. This will enhance the possibility to understand the details of a detected environmental impact. The analysis is based on a Taylor series expansion of the system. (Lenzen et al. 2012; Suh & Heijungs 2007; Acquaye et al. 2011)

3.2 Overall goal and scope

The objective of the assignment was to perform a life cycle assessment of the electricity production from wind energy produced by DD-PMG turbines. The production system was an offshore wind farm with 70 wind turbines, including electrical connections to the onshore grid. It was a full life cycle assessment, including the production of components, as well as the installation, operation (and maintenance) and decommissioning phases of the wind farm. The functional unit was 1 kWh of electricity.

The permanent magnets used in the DD-PMG turbines are NdFeB magnets. To my knowledge, there are no existing LCAs of NdFeB magnets for wind turbine application. Consequently, there was a need to construct an inventory for the permanent magnet production, in order to implement this into the wind farm inventory. This made up a second part of the study.

An important motivation for the study was to find out how the environmental concerns of the mining and processing of neodymium, which is used in the permanent magnets, affected the overall environmental damage related to wind power production. A surge for quantifying these impacts led to the need of a detailed inventory of the production of rare earths. Thus, this work of the production of neodymium metal was planned to be an important contribution of the assessment. This cradle-to-gate study is the third part of this study.

Of the three presented parts of the study, the neodymium metal processing is furthest away from the endpoint of the value-chain of electricity production. Accordingly, I firstly present the inventory of the neodymium metal, so the system boundary increases throughout the rest of this chapter. The inventory of the production of NdFeB magnets is presented secondly, which is where the produced neodymium metal ends up. At last, the inventory of the wind farm is presented.

For the first two analysis, a process-based LCA approach is used. For the last wind farm inventory, an already existing hybrid LCA formed the basis for the inventory, and the monetary IO parts from this study was included as well (Arvesen et al. 2013). This choice will be explained in detail in the corresponding section (3.5.2).

For the process-based (physical) analysis, it was decided that the Arda software was suitable tool. Consequently, the Ecoinvent database was used for constructing the background inventory, and ReCiPe as the LCIA framework.

13 of the 18 midpoint categories from the Recipe framework were included in the study. The results from agricultural land occupation, ionising radiation natural land transformation, urban land occupation and water depletion categories are not considered relevant or interesting for the scope of this study, and is consequently omitted. The 13 included categories are: climate change (GWP), fossil depletion (FDP), freshwater ecotoxicity (FETP), freshwater eutrophication (FEP), human toxicity (HTP), marine ecotoxicity (METP), marine eutrophication (MEP), metal depletion (MDP), ozone depletion (ODP), particulate matter formation (PMFP), photochemical oxidant formation (POFP), terrestrial acidification (TAP) and terrestrial ecotoxicity (TETP). However, as there is no impact assessment characterisation available for the use of the critical rare earths in the metal depletion category of the current ReCiPe framework, it is given little emphasis in the discussion section. In addition, the fossil depletion category is only briefly discussed.

3.3 Production of neodymium metal

3.3.1 System definition

The objective of this part of the thesis was to perform a life cycle assessment of neodymium metal production. For this assessment, I chose one option of production to be able to expand it into the life cycle assessment of a direct-driven wind turbine with permanent magnets containing neodymium metal. I took choices in order to reflect, in the best way possible, the production of the neodymium metal ending up inside these magnets.

I chose a functional unit to be 1 kg of neodymium metal. The literature indicates that the praseodymium co-occurring with the neodymium during the processes step is added as an alloy in almost all NdFeB magnets. This praseodymium will therefore be treated as neodymium, as this seems to be the industry practice of today. I will indicate this with a parentheses notation of praseodymium (Pr) in this section.

The scope is limited to a cradle-to-gate study of the neodymium (Pr) metal production. Modifications need to be done for application of the model for other metals produced. The use of small fractions of dysprosium or other REEs than these is not taken into consideration in this study, as most of the dysprosium is produced at other deposits than the Bayan Obo ore modelled in this study.

I based the system on the REE production from the Bayan Obo ore and Baotou processing plant. The production of REEs is very different from plant to plant. As 54% of the world's RE metals comes from this mine, it was decided that this option served best as a proxy for the metals supplied to the world market. As well, 75% of all permanent magnets are produced in China (Humphries 2013). The Bayan Obo processing scheme also had the best quality of data of the considered RE processing plants.

From the background, we know that the REEs are produced from both monazite and bastnäsite in Bayan Obo. For simplicity, together with data quality considerations, I consider only the bastnäsite concentrate in this project. This also reflects the largest production route.

A flow chart shows the production processes of RE metals from the Bayan Obo ore in the figure 3-1. Figure 3-2 shows the flow scheme considered in my assessment.

I decided on the boundaries of each process stage to fit the available data in the best way possible. The iron and RE beneficiation is therefore one stage only. The same goes for the extraction steps in figure 3-1, which is one stage in my scheme in figure 3-2, as opposed to two stages by for example Sprecher et al. (2014). The reduction stage is however divided into two foreground processes, an electrolysis step and an ingot-casting step as shown in figure 3-3.

I did further assumptions during the formation of the inventory, and this will be presented in the next section. I will also present the allocations performed during the iron beneficiation and solvent extraction.

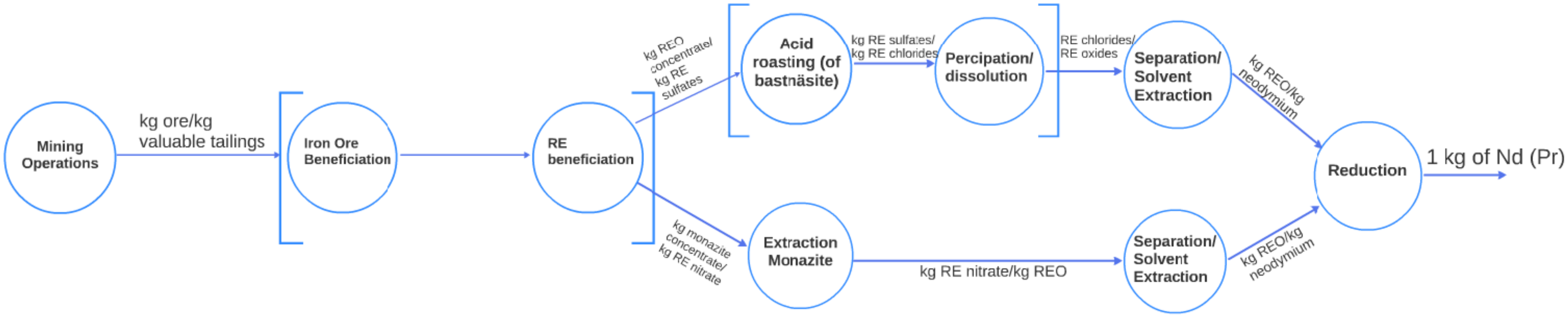

*Figure 3-2, Simplified flowchart of the **actual** process in Bayan Obo*

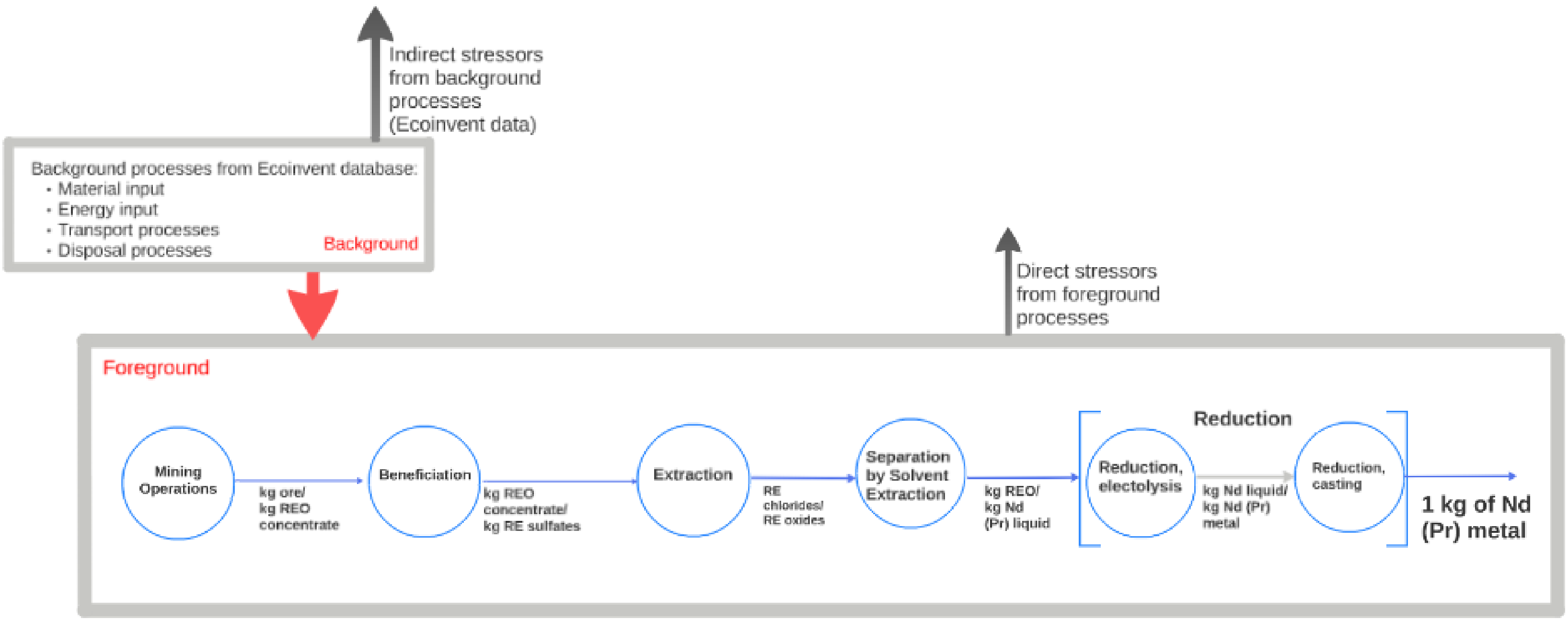

Figure 3-3, Simplified flowchart of the modelled process scheme. Reduction is performed in to steps (see section 3.3.2.2.5).

3.3.2 Inventory

In the following section, I explain the assumptions taken during the construction of the inventory. The first four paragraphs in this section will deal with general issues relevant for all processing stages, the rest of the section will be dedicated to the separate processing stages. The inventory data is quite comprehensive, and there are many assumptions taken. Much of the data is therefore presented in tabular form, to create transparency for the interested reader and keep the text more concise for others.

One limitation of the inventory is that some of the data may be outdated. I have found several articles about new processing techniques, but it has been hard to prove that they have been implemented in commercial production. One example is a new method of extraction by Chi et al. (2004).

3.3.2.1 General issues

Energy processes

All energy processes are modelled as inputs under the corresponding processing stage described in section 3.3.2.2.

All industrial heat energy processes are approximated with the Ecoinvent process *heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER*. It is reported that heavy fuels are used in the Chinese industry (Sprecher et al. 2014). As Ecoinvent includes a process for the consumption of electricity in China, the process *electricity mix/ CN/* is used for this purpose.

Transportation processes

All transport processes are modelled as inputs under the corresponding processing stage described in section 3.3.2.2.

The transportation processes are simplified by the following assumption: the mass of all input materials is considered to be transported a distance of 100 km by road and 600 km rail. This is standard distances for base chemicals (Althaus et al. 2007). The railway distance approximately equals the distance between the processing plant in Baotou and Bejing, and therefore seems to be reasonable. The Ecoinvent processes *transport, lorry >16t, fleet average/ RER* and *transport, freight, rail/ RER* are used. For the latter process the diesel share of (European) railway transport is 40%, while the real Chinese share is closer to 70% (Spielmann et al. 2007). This difference is not considered in this thesis.

The RE processing plant is approximately 130 km from the mining site and milling plant in Bayan Obo. The transportation of the REE concentrate to the processing plant is assumed to be similar to the transportation of coal. This Ecoinvent process *(transport, coal freight, rail/ CN)* is based on Chinese data, and includes the assumption that the REO concentrate is only transported one way, with empty trains returning (Spielmann et al. 2007). There is however a difference in density between coal and the transported concentrate which is not considered in this inventory.

Transport processes are modelled as inputs in the corresponding processing stage.

Composition of ore

There are some differences in the literature about the composition of the ore in Bayan Obo. In this project, I have assumed the same composition of the mine as presented in the Ecoinvent report by Althaus et al. (2007). The report states the REO content of the ore to be 5%.

However other studies report this to be 4,1% or 6% (Sprecher et al. 2014; Drew et al. 1991; Wu 2008). The ore composition is presented in table 3-2.

Allocation issues

During the beneficiation process the iron and niobium content of the ore is extracted, and a RE concentrate prepared. I have chosen an economic partitioning for this process. The individual REE prices in table 5-1 below were gathered from the web page www.metal-pages.com (accessed 08.11.2014). Estimations of the values of the Bayan Obo REEs are presented in table 5-1. From the same web page the niobium content was valued to be 40,5 \$/kg Nb. The value of the iron was estimated to be around 0,2 \$/kg. On the basis of the calculations shown in table 3-1, a share of 0,9 is assumed for the REE content in the iron beneficiation stage.

Table 3-1, Important parameters used for allocation of the beneficiation of the Bayan Obo ore

	Iron	**Niobium**	**REE**	**Reference**
Size of deposit [million tonnes]	1500	1,1	48	(Gupta & Krishnamurthy 2005b)
Weight percentage in the deposit	30,00 %	0,13 %	5,00 %	(Althaus et al. 2007; Drew et al. 1991)
Value in \$/ kg (kilde)	0,20	40,50	21,36	www.metal-pages.com (accessed 08.11.2014)
Mass in kg per kg crude ore	0,30	0,001	0,05	
Value in \$ per kg crude ore	0,06	0,05	1,07	
Estimated partitioning values	0,05	0,04	0,90	

In the solvent extraction stage, the different rare earth elements are separated. I therefore need a partitioning value for the neodymium (and Pr) oxides during this step. I use economic partitioning to allocate the impacts during the solvent extraction. Table 5-2 show important parameters to find this partitioning value of 0,63.

Table 3-2, Important parameters used in the allocation of the separation of the rare earth elements in the Bayan Obo ore. Values were accessed at http://www.metal-pages.com the 8.11.14

	Composi tion	Price of metal per kg	The value per kg REE	Economic allocation	Price of oxides	Values per kg REE
Cerium	50,80 %	$10,00	$5,08		$4,75	$2,41
Lanthanum	26,50 %	$10,50	$2,78		$5,60	$1,48
Neodymium	15,40 %	$83,00	$12,78		$59,50	$9,16
Praseodymium	4,96 %	$150,00	$7,44		$119,00	$5,90
Europium	0,21 %	$1 000,00	$2,10		$720,00	$1,51
Gadolinium	0,60 %	$132,50	$0,80		$46,50	$0,28
Samarium	1,10 %	$26,50	$0,29		$5,50	$0,06
Dysprosium	0,10 %	$470,00	$0,47		$340,00	$0,34
Terbium	0,03 %	$820,00	$0,25		$610,00	$0,18
Yttrium	0,20 %	$60,00	$0,12		$13,50	$0,03
Total	99,90 %		$32,11			$21,36
REE except Nd/Pr	79,21 %		$11,89	0,37		
Nd+Pr	20,36 %		$20,22	0,63		
kg REE produced/ kg Nd+Pr	4,91					
other REE produced/kg Nd+Pr	3,91					

3.3.2.2 Processing stages

Mining

The infrastructural requirements of the iron mine are calculated on the assumptions of the deposit size.

From the Ecoinvent process *rare earth concentrate, 70% REO, from bastnäsite, at beneficiation* (Althaus et al. 2007), we find the dust emissions to be 0,001 kg/kg crude ore. The concentration of iron and individual REEs per kg of crude ore is taken from table 3-1 and 3-2 respectively. They are assumed to be resource stressors from the Ecoinvent database, but the REEs are not considered in the impact assessment of Recipe (Goedkoop et al. 2009b). This would have had an impact in the metal depletion category, and is the reason why metal depletion t is not emphasised in the discussion.

The assumption of 1,4 Bq/kg dust of for the thorium emissions to air is based on the IAEA (2011) report. However, there does not exist any characterisation factors of the isotope of thorium-232. Ionising radiation category is not considered in this thesis, and it does not mattes because of long halftimes, the ionising radiation from the isotope is very small. However, thorium is a heavy metal, and we know from the background theory that it represents an environmental concern. The empty Ecoincent stressor *thorium-232, air, low population density, kBq*, is presented in table 3-3 to indicate the shortcomings in this study, and is ready for implementation in a future research. It is also worth to notice that health risks of workers (in the mine) is not considered as a part of standard life cycle analysis, and is also not considered in this assessment.

Table 3-3, Input and output processes and stressors considered for the mining of the Bayan Obo Ore

Input					
Name	**Ecoinvent name**	**Value**	**Unit**	**Reference**	**Assumptions**
Energy (diesel for trucks)	diesel, burned in building machine/ GLO/ MJ	1,27E-01	MJ/kg ore	Norgate & Haque (2010) (Includes miscellaneous equipment 0.7 kg/t ore)	Iron mining (AUS figures)
Explosives	explosives, tovex, at plant/ CH/ kg	5,00E-04	kg/kg ore	Norgate & Haque (2010)	Iron mining
Iron mine	mine, iron/ GLO/ unit	6,46E-13	-	Althaus et al. (2007)	Number found by total deposit size
Recultivation of mine	recultivation, iron mine/ GLO/ m2	5,33E-07	-	Althaus et al. (2007)	
Output					
Crude ore		1	kg		
Stressors					
Dust, coarse	particulates, > 10 um, air, low population density, kg	5,00E-04	kg	Althaus et al. (2007)	
Dust, medium	particulates, > 2.5 um, and < 10um, air, low population density, kg	4,50E-04	kg	Althaus et al. (2007)	
Dust, fine	particulates, < 2.5 um, air, low population density, kg	5,00E-05	kg	Althaus et al. (2007)	
Th.232 Low population	thorium-232, air, low population density, kBq	1,40E-03	kBq	IAEA (2011)	
Iron	fe, resource, in ground, kg	3,00E-01	kg	calc	
Cerium	cerium, 24% in bastnasite, 2.4% in crude ore, resource, in ground, kg	2,07E-02	kg	calculated from ore composition data	
Lanthanum	lanthanum, 7.2% in bastnasite, 0.72% in crude ore, resource, in ground, kg	5,94E-03	kg	calculated from ore composition data	
Neodymium	neodymium, 4% in bastnasite, 0.4% in crude ore, resource, in ground, kg	3,30E-03	kg	calculated from ore composition data	
Praseodymium	praseodymium, 0.42% in bastnasite, 0.042% in crude ore, resource, in ground, kg	3,42E-04	kg	calculated from ore composition data	
Europium	europium, 0.06% in bastnasite, 0.006% in crude ore, resource, in ground, kg	4,53E-05	kg	calculated from ore composition data	
Gadolinium	gadolinium, 0.15% in bastnasite, 0.015% in crude ore, resource, in ground, kg	1,30E-04	kg	calculated from ore composition data	
Samarium	samarium, 0.3% in bastnasite, 0.03% in crude ore, resource, in ground, kg	2,37E-04	Kg	calculated from ore composition data	
Dysprosium	not found	2,18E-05	Kg	calculated from ore composition data	
Terbium	not found	3,19E-06	Kg	calculated from ore composition data	
Yttrium	not found	3,94E-05	Kg	calculated from ore composition data	

Beneficiation

Table 3-4, Important parameters for the beneficiation stage of the Bayan Obo ore processing

Process parameters		
REO content of concentrate	68,00 %	Krishnamurthy (2005). All REO is assumed to be bastnäsite
Recovery rate	50,00 %	Schüler, Talens Peiró
Partitioning value of the REO concentrate	90,00 %	Calculated

The techniques of beneficiating the REO seems to be in constant development, and the beneficiation process is differently described in all relevant literature (Ren et al. 2000; Althaus et al. 2007). I follow the process scheme described by Gupta & Krishnamurthy (2005a), and a 68% REO concentrate is assumed to be prepared.

The hydroxamic acid is not accounted for, as no suitable Ecoinvent process was found for this chemical. The mass of the hydroxamic acid is however considered in the transportation process. All the other chemicals are fitted to the Ecoinvent processes as displayed in table 3-6. The assumption of the sodium carbonate coming from ammonium chloride production is chosen because it is the sole sodium carbonate process in the Ecoinvent database. This assumption might however deviate from Chinese practice. The values are calculated from the estimation by Althaus et al. (2007) of chemical consumption per tonne ore for the RE beneficiation. There are high uncertainties for the values and poor data quality for the beneficiation stage.

These input processes are only available in the Ecoinvent database in region Europe (RER), thus the chemical input is assumed to be produced with technology similar to the European.

There is reason to believe that there will be some contamination to water resources of heavy metals and other pollutants during this stage. Similar to the approach from Sprecher et al. (2014), the Ecoinvent documentation of the processing of iron is used to model these environmental stressors (Classen et al. 2007). Thus, the ore is approximated as a standard iron ore. In addition, the empty *thorium-232, water, river, kBq* is modelled for the same reasons as for the thorium-232 in the previous section (in the mining stage).

Table 3-5, Output of the beneficiation of the Bayan Obo ore.

Output	Value	Unit
REO concentrate, assumed to be bastnasite	1,00E+00	kg
Iron concentrate, 70% concentrate	1,05E+01	kg
Non-valuable tailings	1,57E+01	kg

Table 3-6, Input processes for the beneficiation of the Bayan Obo ore. Allocation is used for the part of iron ore beneficiation.

Input	Beneficiation part	Ecoinvent process name	Original value	Allocated value	Unit	Reference
Crude ore			2,72E+01	2,45E+01	kg	Calculated
Na2CO3	iron beneficiation	sodium carbonate from ammonium chloride production..	8,16E-02	7,34E-02	kg	Gupta & Krishnamurthy, estimated from Althaus et al.
NaSiO3	iron beneficiation	sodium silicate, spray powder 80%, at plant/ RER/ kg	8,16E-02	7,34E-02	kg	Gupta & Krishnamurthy, estimated from Althaus et al.
Parraffin soap	iron beneficiation	fatty alcohol, petrochemical, at plant/ RER/ kg	2,72E-02	2,45E-02	kg	Gupta & Krishnamurthy, estimated from Althaus et al.
Electricity, crushing/screening	iron beneficiation	electricity mix/ CN/ kWh	8,16E-02	7,34E-02	kwh	Norgate & Haque 2010
Na2CO3, Soda ash	tailing beneficiation	sodium carbonate from ammonium chloride production...	5,02E-02	-	kg	Gupta & Krishnamurthy, estimated from Althaus et al.
NaSiO3	tailing beneficiation	sodium silicate, spray powder 80%, at plant/ RER/ kg	4,30E-02	-	kg	Gupta & Krishnamurthy, estimated from Althaus et al.
Na2SiF6	tailing beneficiation	sodium silicate, spray powder 80%, at plant/ RER/ kg	4,30E-02	-	kg	Gupta & Krishnamurthy, estimated from Althaus et al.
Hydroxamic acid	tailing beneficiation	*No matching process found*	1,67E-02	-	kg	Gupta & Krishnamurthy, estimated from Althaus et al.
Transport for chemicals, rail		transport, freight, rail/ RER/ tkm	2,06E-01	1,95E-01	tkm	Calculated based on transport assumption
Transport for chemicals, road		transport, lorry >16t, fleet average/ RER/ tkm	3,43E-02	3,24E-02	tkm	Calculated based on transport assumption

Table 3-7, Stressors for the beneficiation of the Bayan Obo ore.

Stressors	Beneficiation step	Ecoinvent process name	Original value	Allocated value	Unit
Thorium in tailings	tailing beneficiation	thorium-232, water, river, kBq	2,52E+01	-	kBq
BOD5, Biological Oxygen Demand[water_unspecified]	iron beneficiation	bod5, biological oxygen demand, water, unspecified, kg	1,42E-03	1,28E-03	kg
DOC, Dissolved Organic Carbon[water_unspecified]	iron beneficiation	doc, dissolved organic carbon, water, unspecified, kg	5,15E-05	4,63E-05	kg
TOC, Total Organic Carbon[water_unspecified]	iron beneficiation	toc, total organic carbon, water, unspecified, kg	5,15E-05	4,63E-05	kg
Arsenic, ion[water_unspecified]	iron beneficiation	arsenic, ion, water, unspecified, kg	9,49E-07	8,54E-07	kg
Cadmium, ion[water_unspecified]	iron beneficiation	cadmium, ion, water, unspecified, kg	9,49E-07	8,54E-07	kg
Chromium VI[water_unspecified]	iron beneficiation	chromium vi, water, unspecified, kg	9,49E-07	8,54E-07	kg
Copper, ion[water_unspecified]	iron beneficiation	copper, ion, water, unspecified, kg	4,75E-06	4,28E-06	kg
Cyanide[water_unspecified]	iron beneficiation	cyanide, water, unspecified, kg	9,49E-06	8,54E-06	kg
Iron, ion[water_unspecified]	iron beneficiation	iron, ion, water, unspecified, kg	3,33E-05	2,99E-05	kg
Lead[water_unspecified]	iron beneficiation	lead, water, unspecified, kg	1,90E-06	1,71E-06	kg
Mercury[water_unspecified]	iron beneficiation	mercury, water, unspecified, kg	9,49E-08	8,54E-08	kg
Nickel, ion[water_ground-, long-term]	iron beneficiation	nickel ii, water, unspecified, kg	4,75E-06	4,28E-06	Kg
Oils, unspecified[water_unspecified]	iron beneficiation	oils, water, unspecified, kg	9,49E-05	8,54E-05	kg
Zinc, ion[water_unspecified]	iron beneficiation	zinc, ion, water, unspecified, kg	1,90E-05	1,71E-05	kg

Extraction

The material inputs from the work of Talens Peiró & Villalba Méndez (2013) is matched with processes in the Ecoinvent database. Water use is not considered in this thesis.

The bastnäsite input corresponds to 4,30 kg of the 68% concentrate input.

The output of sulphuric acid and hydrofluoric acid from Talens Peiró & Villalba Méndez (2013) is assumed to be scrubbed with an efficiency of 75%. The uncaptured sulphuric emissions are assumed to be emitted as (unspecific) sulphur trioxide emissions to air. The hydrofluoric acid output is assumed to be emitted to air (in high population density) as hydrofluoric gas. The disposal of a waste stream of sulphidic tailings is also considered. The value used in Sprecher et al. (2014) is adapted to my model. Other emissions regarding the output is not considered.

Table 3-8. Input materials for the extraction of the rare earth concentrate in the Baotou processing plant

Input materials			
Compound	**Process name**	**Value**	**Unit**
Bastnasite		2,92E+00	Kg
Sulphuric acid	sulphuric acid, liquid, at plant/ RER/ kg	2,16E+00	kg
Sodium chloride	sodium chloride, powder, at plant/ RER/ kg	6,03E+00	Kg
Sodium hydroxide	sodium hydroxide, 50% in H2O, production mix, at plant/ RER/ kg	8,02E-01	kg
Hydrochloric acid	hydrochloric acid, 30% in H2O, at plant/ RER/ kg	5,72E-01	Kg

Table 3-9, Other processes considered for the extraction of the rare earth concentrate in the Baotou processing plant

Other processes					
Input	**Process name**	**Value**	**Unit**	**Reference**	**Assumption**
Heavy fuel oil	heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ	8,65E+00	MJ	Talens Peiró & Villalba Méndez 2013	Lime roasting in rotary kiln
Electrical energy	electricity mix/ CN/ kWh	2,37E-02	kwh	Calculated based on transport assumption	Lime roasting in rotary kiln
Transport by rail	transport, freight, rail/ RER/ tkm	5,74E+00	tkm	Transport assumption	
Transport of chemicals by lorry	transport, lorry >16t, fleet average/ RER/ tkm	8,33E-01	tkm	Transport assumption	
Transport of REO concentrate on train	transport, coal freight, rail/ CN/ tkm	3,80E-01	tkm	Transport assumption	
Disposal of sulfidic tailings	disposal, sulfidic tailings, off-site/ GLO/ kg	8,94E-01	kg	Calculated from Sprecher et al.'s (2014) value	

Table 3-10, Direct stressors for the extraction of the rare earth concentrate in the Baotou processing plant

Output stressors			
Output compound	**Stressor name**	**Value**	**Unit**
Sulphuric acid	sulphur trioxide, air, high population density, kg	9,69E-02	kg
Hydrofluoric acid	hf, air, high population density, kg	1,19E-01	kg

Separation by solvent extraction

The organic solvent used in Bayan Obo is assumed to be P507, but is approximated as a more general organic chemical in my study (Schüler et al. 2011; Althaus et al. 2007). The values for the organic solvent use are very uncertain. Estimation of total solvent use ranged from 0,006 to 6,1 kg per kg REO separated, according to a research by EPA in 1998 (Althaus et al. 2007). Althaus et al. (2007) suggest 1 kg organic solvent and 2 kg of solvent medium used per kg REO separated. Talens Peiró & Villalba Méndez (2013) suggest a 3:1 solvent-to-feed ratio to be used, and approximates 7,04 kg of total solvent to be produced per kg individual RE metal produced. There is confusion over the several assumptions undertaken to produce these values, and I do not think that any of the relevant references in the current research address all these clearly.

Some of these assumptions are:

- If the values of chemicals consumption are given considering the recycling rate of the solvents. Large amounts should be recycled (Schüler et al. 2011; MEP 2011). No data is found for the recycling rate.
- The number of extraction stages used is crucial for the use of chemicals and electricity, but is poorly described for the values in the references. In addition, the actual number of stages in Bayan Obo is not known.

I decide upon using the values from Althaus et al. (2007), since this includes a 95% recovery yield for the REEs. These values are 2 kg P507 per kg REO and 1 kg HCl perkg REO. The number of extraction stages is not taken into consideration. 90% of the solvents are assumed to be recycled. 10% of the solvent mixture waste is considered to be disposed as hazardous waste at a waste incineration plant. The disposal process is not documented outside Althaus et al. (2007), but it is considered that the incentives in the Chinese REE industry lead to a need for a disposal process of this kind.

The electricity demand for pumping purposes is also highly dependent on the number of extraction stages needed. This is not known for our analysis, and the electricity usage is based on the estimations from Talens Peiró & Villalba Méndez (2013).

After the stripping step, the now separated RE chlorides are precipitated with ammonium bicarbonate. An estimated value of 1,1 kg ammonium bicarbonate per kg REO is assumed (Schüler et al. 2011). The precipitate is then heated during an oxidation process to form the end product as RE oxides (REO). CO_2 is a product of this oxidation. Based on the chemical reaction, an assumption of 3 moles CO2 produced per mole RE oxides is made, and is emitted to air.

Althaus et al. (2007) model several contaminants from the waste streams of the processing of rare earths. The documentation is poor and old (from 1996) and based on similar American industry. As the figures are considered to be modest, and we know from the background section that contamination of water resources indeed is a problem in Bayan Obo, the figures are chosen to be implemented in the model. Schüler et al. (2011) report that during this precipitation step there is a substantial amount of wastewater generated. It contains ammonia, which is assumed to be emitted to water.

Table 3-11, Important parameters for the separation by solvent extraction of the RE concentrate in the Baotou processing plant

Parameters	
Efficiency	*95 %*
Neodymium cont.	*15 %*
Praseodymium	*5 %*

Table 3-12, Input and output processes for the separation by solvent extraction of the RE concentrate in the Baotou processing plant

Name of actual compound	Name of Ecoinvent Process	Weight	Unit	Allocated values
Input				
RECl3, input feed	Extraction of Bastnäsite concentrate to RE chlorides	5,86E+00	kg	3,69E+00
P507	chemicals organic, at plant/ GLO/ kg	9,82E-01	kg	6,19E-01
HCl	hydrochloric acid, 30% in H2O, at plant/ RER/ kg	4,91E-01	kg	3,09E-01
Ammonium bicarbonate	ammonium bicarbonate, at plant/ RER/ kg	1,10E+00	kg	1,10E+00
Disposal, solvents mixture	disposal, solvents mixture, 16.5% water, to hazardous waste incineration[CH]	1,47E+00	kg	9,28E-01
Electricity	electricity mix/ CN/ kWh	5,34E+00	kWh	3,36E+00
Heat energy for precipation?	heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ	4,90E-01	MJ	4,90E-01
Transport, road	transport, lorry >16t, fleet average/ RER/ tkm	4,69E-01	tkm	2,96E-01
Transport, rail	transport, freight, rail/ RER/ tkm	3,41E+00	tkm	2,14E+00
Output				**Partitioning values**
Nd2O3 (Pr)	neodymium oxide	1,00E+00	kg	6,30E-01
Other REO		4,91E+00	kg	3,70E-01

Table 3-13, Extensive list of all stressors for the separation by solvent extraxtion of the RE concentrate in the Baoutou processing plant.

Name of actual compound	Name of Ecoinvent stressor	Weight	Unit	Allocated values
Ammonia to water	ammonium, ion, water, unspecified, kg	1,08E+00	kg	1,08E+00
CO2 from RE2(CO2)3	carbon dioxide, fossil, air, high population density, kg	2,62E-01	kg	2,62E-01
Aluminium	al, water, river, kg	1,80E-04	kg	1,14E-04
Antimony	antimony, water, river, kg	2,79E-05	kg	1,76E-05
Arsenic, ion	arsenic, ion, water, river, kg	2,54E-06	kg	1,60E-06
Barium	barium, water, river, kg	2,69E-06	kg	1,69E-06
Beryllium	beryllium, water, river, kg	2,77E-07	kg	1,74E-07
Cadmium, ion	cadmium, ion, water, river, kg	2,71E-07	kg	1,71E-07
Chloride	chloride, water, river, kg	3,63E-02	kg	2,29E-02
Chromium, ion	chromium iii, water, river, kg	1,46E-06	kg	9,20E-07
Cobalt	cobalt, water, river, kg	1,49E-07	kg	9,38E-08
Copper, ion	copper, ion, water, river, kg	5,53E-06	kg	3,48E-06
Cyanide	cyanide, free, water, river, kg	2,26E-07	kg	1,43E-07
Fluoride	fluoride, water, river, kg	7,57E-05	kg	4,77E-05
Heat, waste	heat, waste, air, low population density, MJ	7,45E+00	MJ	4,69E+00
Hydrogen fluoride	hf, air, unspecified, kg	3,19E-02	kg	2,01E-02
Iron, ion	iron, ion, water, river, kg	5,13E-05	kg	3,23E-05
Lead	pb, water, river, kg	1,26E-05	kg	7,93E-06
Magnesium	magnesium, 0.13% in water, water, river, kg	1,08E-02	kg	6,78E-03
Manganese	mn, water, river, kg	5,23E-04	kg	3,29E-04
Mercury	mercury, water, river, kg	1,26E-09	kg	7,93E-10
Molybdenum	mo, water, river, kg	2,51E-06	kg	1,58E-06
Nickel, ion	nickel ii, water, river, kg	6,27E-06	kg	3,95E-06
Radium-226	radium-226 (ra-226), water, river, kBq	1,19E-01	kBq	7,48E-02
Selenium	selenium, water, river, kg	2,54E-06	kg	1,60E-06
Silver, ion	silver, ion, water, river, kg	2,61E-06	kg	1,65E-06
Sulfate	sulfate, water, river, kg	5,44E-03	kg	3,43E-03
Sulfide	sulfide, water, river, kg	8,57E-07	kg	5,40E-07
Sulfur dioxide	sulfur dioxide, air, low population density, kg	5,32E-03	kg	3,35E-03
Suspended solids, unspecified	suspended solids, water, river, kg	2,38E-02	kg	1,50E-02
Thallium	thallium, water, river, kg	1,26E-05	kg	7,93E-06
Thorium-232	thorium-232, water, river, kBq	6,03E-01	kBq	3,80E-01
TOC, Total Organic Carbon	toc, total organic carbon, water, river, kg	2,74E-04	kg	1,73E-04
Uranium-238	uranium-238 (u-238), water, river, kBq	1,60E-03	kBq	1,01E-03
Vanadium, ion	vanadium, ion, water, river, kg	2,51E-06	kg	1,58E-06
Zinc, ion	zinc, ion, water, river, kg	4,07E-05	kg	2,57E-05

Reduction

I have based the reduction stage on the Ecoinvent process for primary aluminium production, similar to Sprecher et al. (2014). It is documented in Classen et al. (2007) . It was not found more similar data involving electrolysis of neodymium. However, the different properties of the metals will lead to different requirements within the electrolytic cell. For example, the metals have different melting points, which is 2 233 °C for neodymium oxide versus 2 072 °C for aluminium oxide. Although both are known as unreactive elements, their oxygen affinity is different. This is an weakness for the current model, but as both metals can be reduced by fluoride systems, the aluminium (Hall-Héroult) process is found to be the most available and precise proxy.

I have modelled this stage as two separate steps, as it is done in the Ecoinvent database (Classen et al. 2007) .The first energy-intensive step is the main electrolysis step, called *neodymium reduction, electrolysis*. This is producing the pure neodymium (Pr) liquid in the electrolyte. The material and other inputs from is assumed to have similar environmental impacts as the Ecoinvent process *aluminium, liquid, at plant*. The same inputs are therefore used, but are adjusted by a weight factor. The anode and cathode are adjusted on a mole basis. The Ecoinvent input of aluminium oxide is replaced by my foreground solvent extraction process, which produces neodymium (Pr) oxide. The output of the process is 1 kg of neodymium (Pr) liquid metal.

The assumption of similar technology as aluminium is also used for the ingot casting step, called *neodymium reduction, casting* in my model. During this final step, the liquid metal solidifies to a physical product. The Ecoinvent process *aluminium, primary, at plant* includes this ingot casting step. The aluminium liquid input is replaced by the neodymium (Pr) liquid. Since there is no weight difference no other inputs are changed. The output of the process is 1 kg of neodymium (Pr) metal.

The value of required heat energy for the electrolytic cell (in *neodymium reduction, electrolysis*) is based on the work by Sprecher et al. (2014), and the electricity demand for this step is based on Talens Peiró & Villalba Méndez (2013). For the final ingot casting step the same values are based on the Ecoinvent process.

Table 3-14, Input processes for the reduction of the neodymium by electrolysis in the Baotou processing plant

Process name	Process #	Value	Unit
neodymium oxide	-	1,20E+00	kg
cryolite, at plant/ RER/ kg	480	9,87E-04	kg
aluminium fluoride, at plant/ RER/ kg	1752	1,15E-02	kg
anode, aluminium electrolysis/ RER/ kg	1763	8,37E-02	kg
cathode, aluminium electrolysis/ RER/ kg	1776	3,38E-03	kg
disposal, inert waste, 5% water, to inert material landfill/ CH/ kg	3078	3,08E-03	kg
disposal, filter dust Al electrolysis, 0% water, to residual material land…	3284	1,23E-03	kg
disposal, refractory SPL, Al elec.lysis, 0% water, to residual material la…	3305	1,17E-03	kg
disposal, bitumen, 1.4% water, to sanitary landfill/ CH/ kg	3320	7,40E-04	kg
aluminium electrolysis, plant/ RER/ unit	3714	9,50E-11	unit
heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ	2394	4,49E-02	MJ
electricity mix/ CN/ kWh	901	1,28E+01	kWh
transport, lorry >16t, fleet average/ RER/ tkm	2807	1,06E-02	tkm
transport, freight, rail/ RER/ tkm	2887	6,35E-02	tkm

Table 3-15, Stressors for the reduction of the neodymium by electrolysis in the Baotou processing plant

Stressor name	Value	Unit
carbon dioxide, fossil, air, high population density, kg	2,81E-01	kg
nox to air, air, high population density, kg	6,39E-05	kg
heat, waste, air, high population density, MJ	5,60E+01	kg
hf, air, high population density, kg	5,39E-04	kg
particulates, < 2.5 um, air, high population density, kg	2,61E-03	kg
particulates, > 2.5 um, and < 10um, air, high population density, kg	6,09E-04	kg
so2 to air, air, high population density, kg	8,83E-03	kg
benzo[a]pyrene, air, high population density, kg	1,30E-06	kg
carbon monoxide, fossil, air, high population density, kg	1,72E-02	kg
pfc-116, air, high population density, kg	2,80E-05	MJ
pfc-14, air, high population density, kg	2,52E-04	kg
pah, polycyclic aromatic hydrocarbons, air, high population density, kg	4,57E-05	kg

Table 3-16, Input processes for the casting during the reduction of the neodymium in the Baotou processing plant

Process name	Value	Unit
argon, liquid, at plant/ RER/ kg	1,50E-03	kg
chlorine, liquid, production mix, at plant/ RER/ kg	1,00E-04	kg
cryolite, at plant/ RER/ kg	4,00E-04	kg
nitrogen, liquid, at plant/ RER/ kg	6,00E-04	kg
palm oil, at oil mill/ MY/ kg	8,00E-05	kg
refractory, fireclay, packed, at plant/ DE/ kg	7,00E-04	kg
rock wool, at plant/ CH/ kg	1,10E-04	kg
MG-silicon, at plant/ NO/ kg	1,08E-02	kg
neodymium reduction, electrolysis	1,00E+00	kg
corrugated board, mixed fibre, single wall, at plant/ RER/ kg	1,80E-03	kg
disposal, inert waste, 5% water, to inert material landfill/ CH/ kg	9,90E-04	kg
disposal, dross from Al electrolysis, 0% water, to residual material landfill/ CH/ kg	1,10E-04	kg
aluminium casting, plant/ RER/ unit	1,54E-10	-

Table 3-17, Stressors for the casting during the reduction of the neodymium in the Baotou processing plant

Stressor name	Value	Unit
water, river, resource, in water, m3	4,71E-03	kg
heat, waste, air, high population density, MJ	5,76E-02	kg
hf, air, high population density, kg	3,00E-06	kg
particulates, > 2.5 um, and < 10um, air, high population density, kg	7,00E-06	kg

3.4 Production of NdFeB magnets

3.4.1 System definition

For this part of the thesis, the goal was to assess the NdFeB magnet production. The previous work on neodymium metal was going to be implemented in the study. A further objective was to adopt this analysis into the larger assessment of wind power.

A functional unit of 1 kg NdFeB magnet was suitable for the implementation into the wind turbine section of the inventory. This assessment is a cradle-to-gate study at a given production site. A flowchart (figure 3-2), indicating the system boundaries, can be found on the next page. The sintered magnet production route was chosen. These magnets are most frequently used, and had the best data availability.

3.4.2 Inventory

The most comprehensive and updated data for rare earth permanent magnets is found in the work of Sprecher et al. (2014). The data provided in the supporting information of his article is exclusively used to construct the inventory of the magnet production. The magnet is assumed to contain 27% neodymium metal, 72% iron and 1% boron.

It is worth noticing that the stressors related to the sintering stage are based on the data from an iron sintering process from the Ecoinvent database (*sinter, iron, at plant/ GLO/ kg*).

The neodymium metal is assumed to be transported 2100 km by train, as assumed in Sprecher et al.'s article. The 50% weight increase due to packaging materials is also included. The production is assumed to take place in Ningbo Konit, where the main part of production of NdFeB magnets in China is situated.

For consistency with the REE inventory, the transportation of the material inputs is also considered in this study. They are assumed to be transported 200 km by train and 50 km by lorry. Shorter transportation distances are considered in this part of the inventory, compared to the previous section, since Ningbo is placed at the industrial centre at the eastern coast of China.

No Ecoinvent process was found for hydrogen gas during the hydrogen decrepitation stage. Sprecher et al. (2014) based the hydrogen consumption on electrolysis of water. I have rather used the common hydrogen liquid process from the Ecoinvent database (*hydrogen, liquid, at plant/ RER/ kg*). It represents the average European production mix of hydrogen (Althaus et al. 2007).

There are differences in grinding losses between the smaller magnets used in HDDs and the larger magnets in wind turbines. The losses should be lower for the large magnets, and an approximate value of 10% lost material replaces the assumption of 30% loss in the study by Sprecher et al. The share that is recycled is still assumed to be 50% of the lost material. The energy consumption was not altered, and is assumed to 1,4 kWh per kg of grinded NdFeB magnet.

There is need for a protective coating of the magnets. Electroplating of the magnets with a nickel coating is assumed. This is similar to Sprecher et al (2014). The nickel coating process during the electroplating stage is constructed from data from a separate source (Moing et al. 2009). The surface area is assumed to be 0,07 m2 per kg magnet in the study by Sprecher et al.' (2014), with the average hard disk drive (HDD) magnet being 0,5 kg. In our study the mass of NdFeB magnet is assumed to be 3 014 kg. The surface area of these magnets are also larger. The increased surface area is less than the mass increase. Thus, the coating required per kg magnet will be less. The surface area increase is assumed to follow the square-cube law:

$$\frac{A_1}{A_2} = (\frac{V_1}{V_2})^{\frac{2}{3}} = (\frac{m_1}{m_2})^{\frac{2}{3}} \qquad \text{(Eq. 3-1)}$$

The nickel coating is assumed to be 0,004 m2 of coating per kg of coated NdFeB magnet. The mass input of NdFeB to the electroplating stage was also increased from 0,9 kg to 0,989 kg per kg NdFeB magnet. This is a result of the lower requirement of nickel coating mass per kg magnet

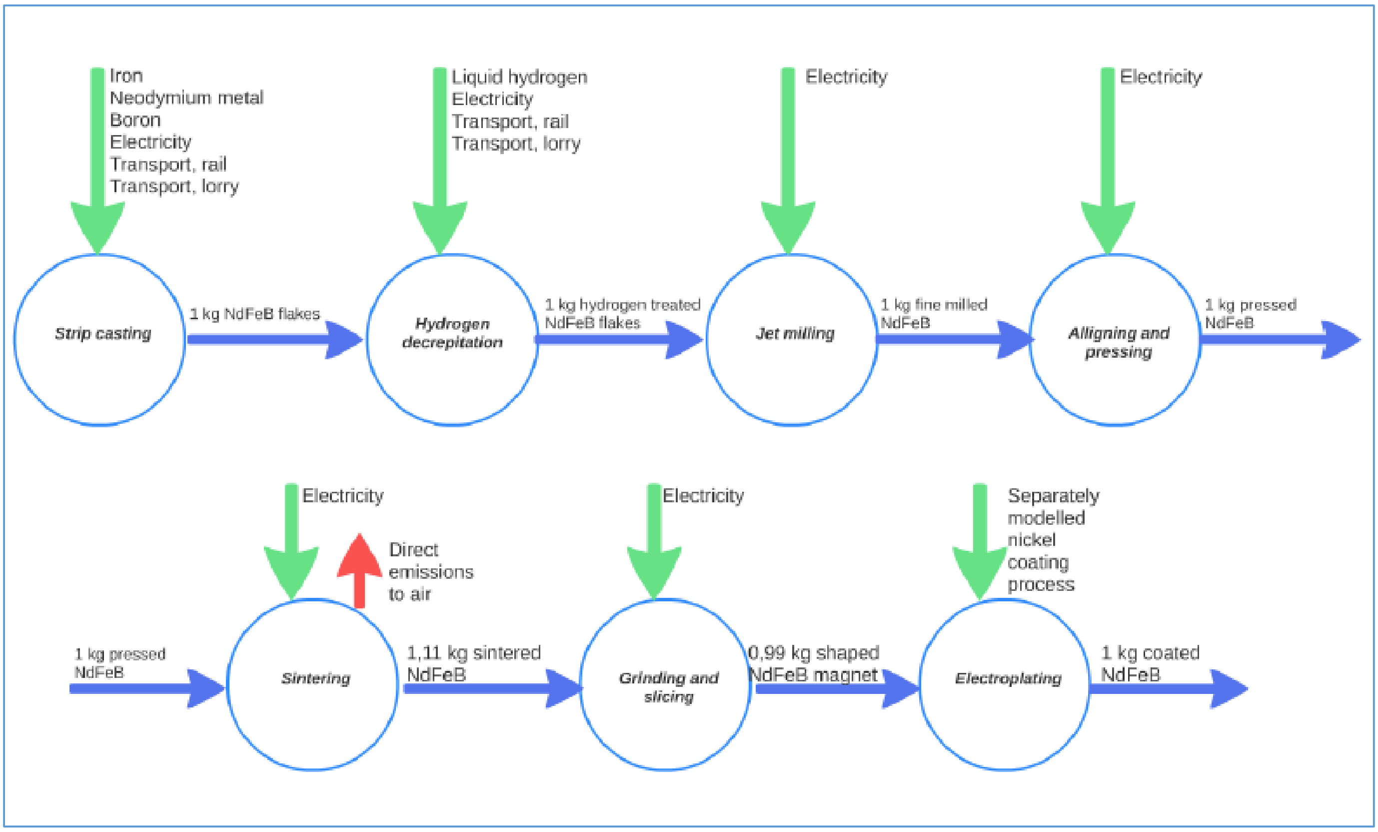

Figure 3-4, flowchart of the production of neodymium magnets.

3.5 Production of electricity from offshore DD-PMG wind turbines

3.5.1 System definition

The goal of this part of the thesis was to perform a life cycle assessment of the production from wind energy produced by the DD-PMG turbines. One objective was to evaluate how the NdFeB magnets affected the environmental performance of the wind turbine park. However, addressing the overall performance of the new wind turbine design will be the main objective in the finalising part of this thesis.

1 kwh of electricity was found to be an appropriate functional unit.

As the thesis seeks to address the benefits and concerns with the direct-drive permanent magnet generators (DD-PMG), a comparative approach with an existing inventory using conventional technology is chosen. The offshore windmill farm inventory published in Arvesen et al. (2013) is used as a model. An equal inventory of this was constructed, called "the conventional turbine"-inventory, to compare with a modified inventory for the DD-PMG turbine. Both were assessed in the Arda software. Emphasis for the discussion of the results are put on the new insights provided by the current assessment, meaning that the environmental impacts distinguishing the current technology compared to the conventional technology will be weighted.

The detailed inventory was a case study of a proposed wind farm called Havsul 1 in western Norway. The study included 70 wind turbines with 5 MW capacity. The aims of the paper was ".. to provide insight into the contribution of installation, operation, and maintenance (O&M), including operations by marine vessels and replacement of parts, to the life cycle impacts of offshore wind power". Empirical data for the O&M phase was scarcely covered by the offshore wind power LCAs at the time of publication.

A detailed inventory of the electrical connections was included in the study. It involved two offshore high voltage (HV) transformers (with helipads and substructure), offshore cabling and onshore connections to grid, in addition to wind mills with substructures. Transportation for End-of-Life (EOL) for the wind mills were also considered. Key data for the Havsul 1 wind farm is displayed in table 3-18. In addition, the lifetime of the wind farm was chosen to be 25 years.

Table 3-18, Key data for the Havsul 1 offshore wind farm. Source: Arvesen et al. (2013)

Key data for the Havsul 1 offshore wind farm	
Wind farm capacity	250 MW
Wind turbine capacity	5 MW
Full load hours, excl. loss and downtime	3000 h
Loss, grid connection	3,1 %
Reduction in generation due to downtime	4 %
Annual electricity to grid	982 GWh
Foundation concept	gravity-based
Internal cabling (33 kV), length	63,3 km
No. of offshore transformer stations	2
Cabling to shore (132 kV), length	54 km
Onshore overhead line, length	8,2 km
Onshore underground cable, length	0,4 km

Adjustments to the current inventory were made where the DD-PMG technology differs from the conventional, mostly affecting the part of the inventory concerning the wind turbine units. Differences in the inventories will be accounted for in the following sections.

3.5.1.1 A purely process-based LCA or a hybrid process and input-output-based LCA?

The original study (Arvesen 2013) used a hybrid LCA model. The physical inventory was from the Ecoinvent database, while monetary inventories from the environmentally extended input output (IO) tables developed for the EXIOPOL (n.d.) project. Monetary inputs that were already covered in the physical inventory were removed by setting the relevant monetary entries to zero. This was done to avoid double counting.

A hybrid approach is also applied in the current study. However, the emphasis for my work so far has been on the physical inventory. There has been a process-based approach to the permanent magnet and rare earth metal processing parts of the study. For the monetary (IO) part of the study, at the current aggregation level, the two different wind turbines are considered to have equal costs. Thus, the input output results from the study by Arvesen et al. (2013) can be treated as extensions to the process-based results in my study. Changes affecting the IO part of the study are presented in this section. Implementing the IO part in this study allows verification and comparisons with the paper by Arvesen et al. (2013).

However, the discussion section of the paper will mostly deal with the process-based results of the wind turbine system. I consider this reasonable, because the physical systems has been emphasised in the assessments of neodymium and NdFeB magnet, and it is in the physical inventory the most interesting differences with the conventional turbine is found, at least for the scope of this study. Thus, we will be comparing with the physical process-based results from the conventional turbine in Arvesen et al. (2013) in the discussion. It is worth noticing that the hybrid methodology can capture environmental impacts of system flows that are omitted in the bottom-up process-based LCA approach (Arvesen et al. 2013). Thus, considering the hybrid LCA results is important when the total impact of the DD-PMG turbine system is examined.

3.5.2 Inventory

3.5.2.1 Materials in nacelle

In a direct-drive turbine, there is no gearbox. In the current analysis, the gearbox is therefore omitted.

The weight of the nacelle was assumed to be consistent with the state-of-the-art planned Siemens D6 platform. From a press release, the nacelle of the 6 MW offshore DD turbine is estimated to have a weight around 230 tons (Siemens AG 2014). According to a presentation by Henrik Stiesdal, then CTO of Siemens Wind Power, at the Coil Winding, Insulation & Electrical Manufacturing Exhibition 2014 in Berlin (CWIEME Berlin 2014), the generator itself weights approximately 100 tons. The two values are scaled down from 6 MW to estimate a direct-drive 5 MW turbine.

3.5.2.2 Generator

The NdFeB material used in the rotor of the current turbine is approximated. The DD-PMG turbine manufacturer "The Switch" supplied a curve of estimated PM material used in the generator. It is given as the mass of NdFeB-material by the rated torque of the turbine. An almost linear increase of PM material with respect to the nominal power of the turbine is observed. The data range is only up to 4,25 MW, so an extrapolation is performed to find the

PM material used in a 5 MW turbine. An approximate value of 3,01 tons is established as the weight of the NdFeB magnet.

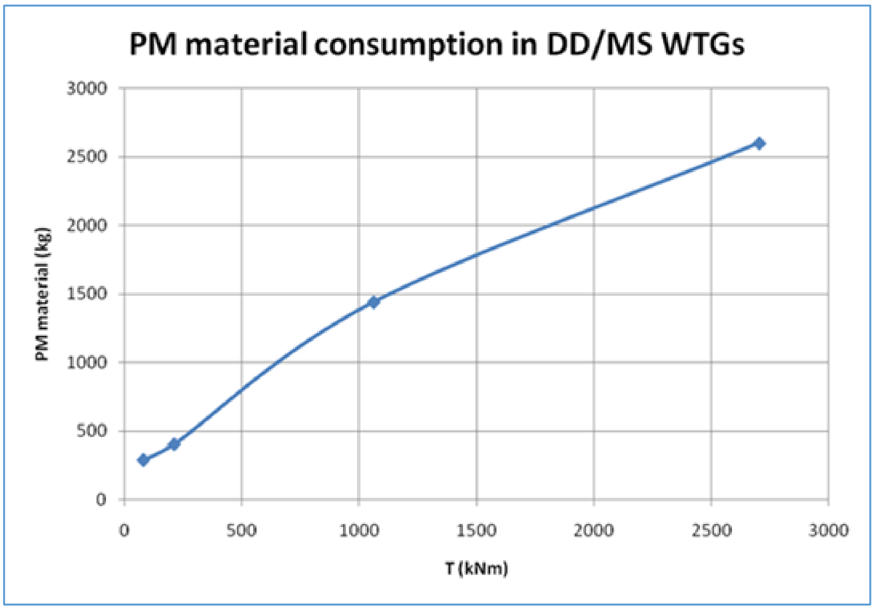

Figure 3-5, Graph displaying the PM material (in kg) used in direct-drive and medium speed wind turbine generators by the rated torque (kNm). My supervisor Anders Arvesen received the graph from personal communication with Panu Kurronen in the Switch (10.01.11).

In addition to the permanent magnet material in the rotor, the assumption of the copper share in the generator is important. This share will be lower than in the conventional, due to the fact that the PMs are replacing the copper coils as the active magnetic material in the rotor. In discussion with academic expertise within the wind turbine field, it was pointed out that roughly half the copper in the conventional generators is in the rotor. The other half is in the stator. Most of the copper is a part of this *active weight* of the generator.

Insights from currently unpublished work on DD-PMGs at NTNU, which is a further development of the work by Zhang et al. (2013), shows that the copper mass for the PM generator will be relatively low. The results from their detailed analysis for optimisation of turbines between 6-10 MW shows a copper share ranging from 5-7% for the modelled turbines. They find that the copper mass in most cases is around two times as large as the PM mass. By doubling the PM mass of our current turbine, we find that the generator requires 6,03 tons of copper. Both the PM share (3,62%) and the copper share (7,23%) of the current study have similar figures to the findings of the unpublished work, but is in the higher range of the found values. The total copper and PM share in the unpublished work is in the range of app. 7,5%.-9,5%. It is worth noticing that there is no correlation for the copper and PM shares with the increasing turbine sizes, and the shares changes quite randomly within the interval. Different designs emphasise different advantages, with raw material prices or other optimization parameters affecting the specific design of the turbine model. Innovation is high for the DD-PMG technology, and the variation is expected to be high for the material used in commercial designs.

The rest of the generator, including all inactive weight, is approximated to consist of the same steel material as in the conventional turbine.

As a part of a sensitivity analysis, a scenario with a higher copper share is analysed. The copper share is reduced to half of the conventional turbine, since there is only copper in the stator. This assumption corresponds to a similar generator as a conventional, with the conventional rotor with copper coils changed for a rotor with permanent magnets. The copper mass for this scenario is 12,8 tons.

3.5.2.3 Other components

The weight of the other components (housing, main frame, main shaft and transformer) inside the nacelle is given by the difference in the already presented values of the generator and the total nacelle weight The weight of these other components represent a weight reduction of 11,75% compared to the conventional design. This is taken to represent the increased compactness of the nacelle, since reports say that a simpler, more straightforward design allowed in the nacelle will lead to weight reductions in the direct drivetrain (Siemens AG 2013; Scott Semken et al. 2012). However, the weight distribution between these other components of the nacelle is assumed equal to the conventional design. Also, the materials used in these components is assumed to be used in the same ratio as in the conventional design. The weight distribution between the components of the nacelle can be found in table 3-19.

Table 3-19, The absolute mass distribution of the materials and components in the conventional (top) and DD-PMG turbine (middle). Relative weights of the distribution between the turbines are also given (bottom).

CONVENTIONAL TURBINE FROM ARVESEN (2013)									
MATERIAL	**Matched process in Ecoinvent**	***Unit***	**Generator**	**Gearbox**	**Housing**	**Main frame**	**Main shaft**	**Transformer**	**TOTAL**
CAST IRON	**cast iron, at plant/ RER/ kg**	***kg***		41 703		35 259			**76 962**
HIGH-ALLOY STEEL	**chromium steel 18/8, at plant/ RER/ kg**	***kg***		41 703			27 029		**68 732**
COPPER	**copper, at regional storage/ RER/ kg**	***kg***	10 426					7 819	**18 245**
GLASS REINFORCED PLASTIC	**glass fibre reinforced plastic, polyamide, injection moulding, at plant/ RER/ kg**	***kg***			10 426				**10 426**
LOW ALLOY AND ELECTRICAL STEEL	**steel, low-alloyed, at plant/ RER/ kg**	***kg***	23 406			19 476	4 770	17 984	**65 636**
TOTAL MASS	-	***kg***	**33 831**	**83 406**	**10 426**	**54 735**	**31 798**	**25 804**	**240 000**

DD-PMG TURBINE									
MATERIAL	**Matced process in Ecoinvent**	***Unit***	**Generator**	**Gearbox**	**Housing**	**Main frame**	**Main shaft**	**Transformer**	**TOTAL**
CAST IRON	**cast iron, at plant/ RER/ kg**	***kg***			0	31 115	0	0	**31 115**
HIGH-ALLOY STEEL	**chromium steel 18/8, at plant/ RER/ kg**	***kg***			0	0	23 852	0	**23 852**
COPPER	**copper, at regional storage/ RER/ kg**	***kg***	6 029		0	0	0	6 900	**12 929**
GLASS REINFORCED PLASTIC	**glass fibre reinforced plastic, polyamide, injection moulding, at plant/ RER/ kg**	***kg***			9 200	0	0	0	**9 200**
LOW ALLOY AND ELECTRICAL STEEL	**steel, low-alloyed, at plant/ RER/ kg**	***kg***	74 290		0	17 187	4 209	15 870	**111 556**
NDFEB-MATERIAL	-	***kg***	3 014						**3 014**
TOTAL MASS		***kg***	**83 333**	**0**	**9 200**	**48 301**	**28 061**	**22 771**	**191 667**

RELATIVE WEIGHTS IN DD-PMG TURBINE COMPARED TO CONVENTIONAL TURBINE									
MATERIAL	**Matced process in Ecoinvent**	***Unit***	**Generator**	**Gearbox**	**Housing**	**Main frame**	**Main shaft**	**Transformer**	**TOTAL**
CAST IRON	**cast iron, at plant/ RER/ kg**	***kg***		0 %		88 %			**40 %**
HIGH-ALLOY STEEL	**chromium steel 18/8, at plant/ RER/ kg**	***kg***		0 %			88 %		**35 %**
COPPER	**copper, at regional storage/ RER/ kg**	***kg***	58 %					88 %	**71 %**
GLASS REINFORCED PLASTIC	**glass fibre reinforced plastic, polyamide, injection moulding, at plant/ RER/ kg**	***kg***			88 %				**88 %**
LOW ALLOY AND ELECTRICAL STEEL	**steel, low-alloyed, at plant/ RER/ kg**	***kg***	317 %			88 %	88 %	88 %	**170 %**
NDFEB	-	***kg***	only in DD-PMG						
TOTAL MASS		***kg***	**246 %**	**0 %**	**88 %**	**88 %**	**88 %**	**88 %**	**80 %**

3.5.2.4 Increase in energy production

As pointed out in section 2.1.3, since the permanent magnet generators has a higher operational flexibility, the electricity production will increase. The following references was considered in the study:

Table 3-20, Proposed values for the increase in the annual energy yield for PMGs from two different references.

	RATED WIND SPEED [M/S]	ENERGY YIELD INCREASE
(KURRONEN ET AL. 2010)	8,2	3,00 %
	6,8	4,30 %
	5,4	8,50 %
(POLINDER ET AL. 2006)	7	4,01 %

We confirm that the values are in compliance. An annual energy yield increase of 3% was found to be an appropriate value for the rated speed of 8 m/s at the Havsul wind farm. The subsequent change in the electricity power production over the lifetime leads to several changes in the foreground requirements with units per kWh compared to the original inventory. With the input output extensions of the study also given as impact per kWh, these values were altered according to the increased number of kilowatt hours produced.

3.5.2.5 Replacement

In the study by Arvesen et al. (2013), the replacement of parts was modelled as two parts: one for the replacement of large parts and one for the replacement of small parts. The latter was not altered for the *reference scenario* for the current study.

The replacement of the large part was performed at an annual rate of 0,075 in the conventional turbine study, where the large part was approximated to be 1/3 set of 2 rotor blades, 1/3 generator and 1/3 gearbox. The gearbox portion is omitted in the current study, similar to the assumption taken for the material distribution in the nacelle, consequently the weight of the large replacement proxy part is smaller for the DD-PMG turbine. The difference in total mass of the large replacement proxy part between the designs, a 23% reduction, reflects the weight difference for the nacelle between the designs, which is 20%.

3.5.2.6 Sensitivity analysis by scenarios

Maintenance: Failure rates and downtime

As seen in section 2.1.4, there was some uncertainty about how the literature reflected the actual state of the direct-drive, and none of the articles found presented solid data suited for the current inventory. Instead, a set of scenarios was developed, and a sensitivity analysis was to be performed, to account for the different perspectives regarding maintenance and reliability. The different assumptions used in the different scenarios are:

1. A decrease in downtime, from 4% to 2,5% and 3% downtime, because of the elimination of the gearbox and fewer wear-prone parts in the direct drivetrain (Siemens AG 2013). A reduction in downtime will affect the annual energy production in the system.
2. An increase in downtime because of increased converter failures. An increase from 4% to 5% is added to account for the uncertainty regarding the reliability of the system. The increase may however be unlikely as the converter failures on average leads to a shorter period of downtime compared to the gearbox failures (Crabtree 2012). The turbines can also partially operate during some of the failures.
3. A maintenance decrease because of the elimination of the gearbox. Crabtree (2012) reports that 6,7% of all failures are gearbox failures. A 7% decrease from the original values in the foreground processes *vessel for maintenance of turbines during operation* and *transport, helicopter (O&M)* is assumed.
4. From figure 2 in Crabtree (2012), one find that the annual stop frequency because of the converter is similar to that of the gearbox. Consequently, a doubling of converter failures, indicated by some references in section 2.1.4, is simply approximated to lead to a 7% increase in the operational maintenance processes from the previous bullet point.
5. The original maintenance requirements of the wind turbines correspond to four maintenance incidents for each wind turbine each year (Arvesen et al. 2013). The Havsul I license application report indicates scheduled maintenance 2 times a year. However, others, e.g. Rademakers & Braam (2002), claims that this could be reduced to one time a year. A goal for the industry is to assure a more reliable operation in order to decrease the costs of maintenance. A decrease by 25% (to three maintenance incidents) is therefore assumed in the optimistic scenario for the operational maintenance processes.
6. For some of the more pessimistic scenarios, it is assumed an increase in the replacement of small part for the direct-drive design. It is a possible result of the increased converter failures (or other unexpected failures or repairs). A 2,5% and 5% increase of the replacement rate is assumed.

Table 3-21, Relation between assumptions and the 6 different scenarios in sensitivity analysis. The assumptions were presented on the previous page.

	Assumption no.					
	1	*2*	*3*	*4*	*5*	*6*
	Assumption used					
Scenario	**Downtime decrease**	**Downtime increase**	**Operational maintenance decrease**	**Operational maintenance increase**	**Scheduled maintenance decrease**	**Small part replacement increase**
Optimistic	X		X		X	
Moderate - optimisitc	X		X			
Moderate	X					X
Moderate - maintenance increase	X		X	X		X
Moderate - pessimistic				X		X
Pesimistic		X		X		X

Table 3-22, Changes in the windmill inventory for the 6 different scenarios. In the top rows, the processes or parameters in the inventory is shown connected to their related assumptions. The values for the downtime represents the actual assumption of the annual downtime. For the three columns to the right, the values represent the relative changes from the original values from the inventory in Arvesen et al. (2013).

	Assumption no.			
	1,2,5	***3,4***	***3,4***	***6***
	Altered process or parameter			
Scenario	**Downtime**	**Vessel for maintenance of turbines during operation**	**Transport, helicopter (O&M)**	**Replacement, small part**
Optimistic	2,50 %	-32,00 %	-32,00 %	
Moderate - optimistic	3,00 %	-7,00 %	-7,00 %	
Moderate	3,00 %			2,50 %
Moderate - maintenance increase	3,00 %	7,00 %	7,00 %	2,50 %
Moderate - pessimistic	4,00 %	7,00 %	7,00 %	2,50 %
Pesimistic	5,00 %	14,00 %	14,00 %	5,00 %

4 Results and discussion

4.1 Production of neodymium metal

Table 4-1, Total impact of the production of 1 kg neodymium metal. Normalised results of the impact is included. Normalisation factors are found in Goedkoop et al. (2009b), and are simply divided by the total impact.

Name of environmental category	Unit	Value	Normalised value [p/yr]
Climate change	kg CO2 eq	6,42E+01	9,31E-03
Fossil depletion	kg oil eq	1,80E+01	1,39E-02
Freshwater ecotoxicity	kg 1,4-DB eq	6,57E-01	1,52E-01
Freshwater eutrophication	kg P eq	2,31E-02	7,98E-02
Human toxicity	kg 1,4-DB eq	1,75E+02	1,49E+00
Marine ecotoxicity	kg 1,4-DB eq	6,35E+00	2,64E+00
Marine eutrophication	kg N eq	1,04E+00	1,42E-01
Metal depletion	kg Fe eq	1,44E+02	3,24E-01
Ozone depletion	kg CFC-11 eq	5,99E-06	1,59E-04
Particulate matter formation	kg PM10 eq	3,92E-01	2,78E-02
Photochemical oxidant formation	kg NMVOC	2,71E-01	5,53E-03
Terrestrial acidification	kg SO2 eq	5,03E-01	1,32E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	8,84E-03	1,36E-03

From table 4-1, we see that the marine ecotoxicity and human toxicity has the highest normalised impacts. They are one order higher than for metal depletion, having the third highest normalised impact. The results will be thoroughly discussed in the rest of this section.

4.1.1 General observations

4.1.1.1 Extraction stage dominates many impact categories – together with solvent extraction

The human toxicity potential (HTP) category has the second highest normalized impact (table 4-1). The direct HF-emissions from the acid roasting during the extraction stage are 80% of the total impacts. The disposal of sulphidic tailings from the same stage has a minor contribution in this category (5%). It is, however, the largest contributor in the freshwater eutrophication category (27% of total impacts). In the most of the toxicity categories, as well as in the terrestrial acidification and freshwater eutrophication categories, the extraction stage dominates (figure 4-1). Disposal processes related to coal mining activities for electricity consumption, from both direct consumption in the processing stage and from production of material inputs, are the most important contributors. In the terrestrial acidification category, the SO_2-emissions during production of sulphuric acid cause 24% of the impact.

In the terrestrial ecotoxicity category, the disposal of solvents mixture from the solvent extraction stage is the largest path (19 % of total impacts). Still the extraction stage is the most dominant of the processing stage (47% of total impacts), due to the hydrochloric acid production (12% of total impacts, mostly chlorine emissions) and from the heavy fuel oil consumption (9%).

In the marine eutrophication and ecotoxicity, the solvent extraction is the dominating stage, with respectively 92% and 98% of the total impacts. The modelled emissions of ammonia (for eutrophication) and cobalt (for ecotoxicity) during the solvent extraction stage is responsible for just about all of the total impact.

4.1.1.2 Concern about particulate forming and diesel consumption during mining

The mining stage is dominant for the particulate matter formation potential category (PMFP) with 66% of total impacts. Most of this is related to the direct dust emissions in this stage (60 % of total impacts). The diesel consumption during the mining stage is ranked as the top process (27 % of total impacts) in the photochemical oxidant formation category. The hard coal from the Chinese power production is the other large contributor (26 %). Most of the impacts are related to value chains connected to energy consumption, however sulphuric acid production (5 %) and production of the fatty alcohol during beneficiation (5%) are minor contributors.

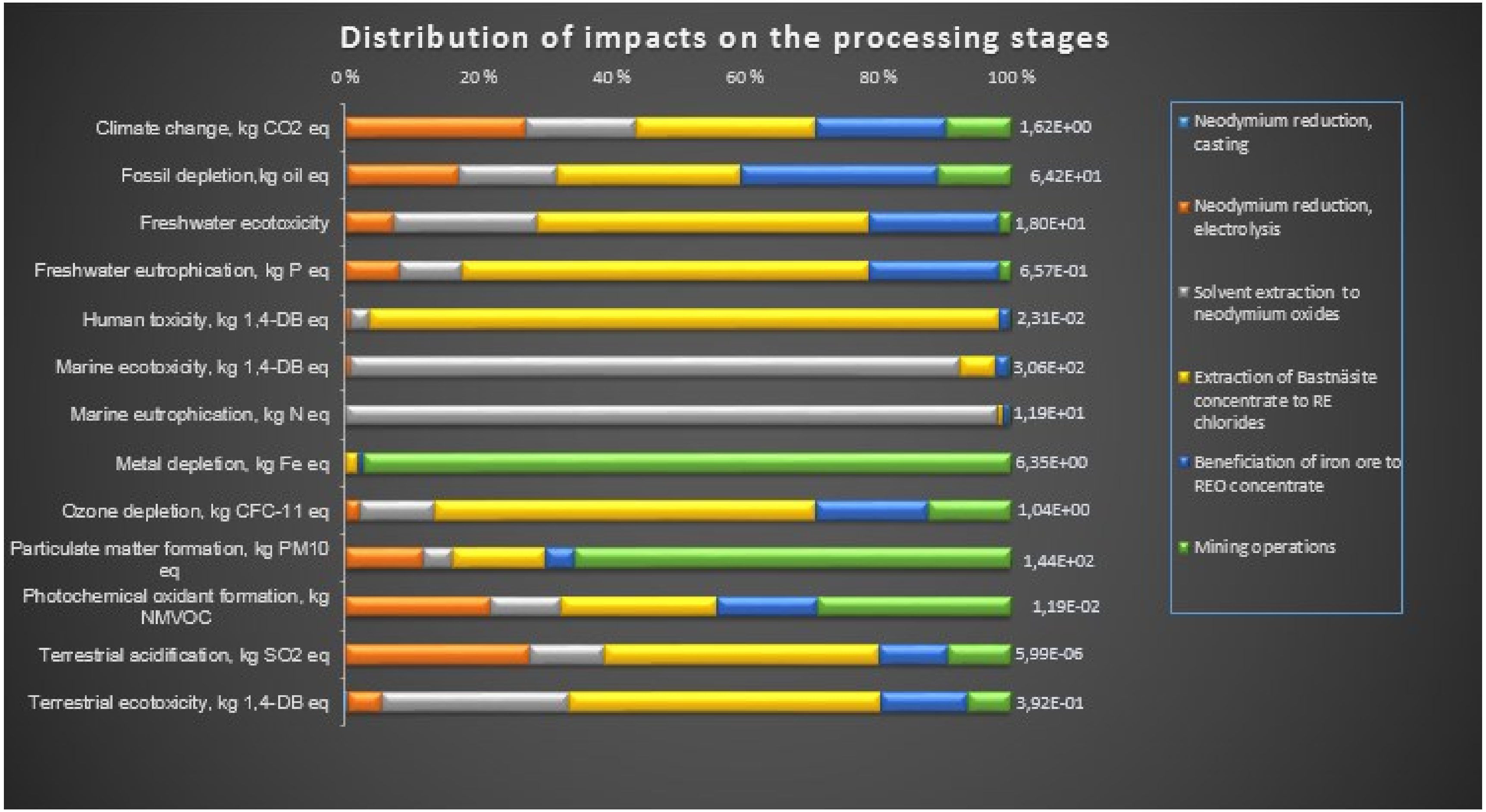

Figure 4-1, Graphical representation of the distribution of impact on the processing stages. Absolute values of impact are indicated on right side of the chart. Impact categories with units are in the left column.

4.1.2 Climate change category

4.1.2.1 Large impacts related to electricity consumption

Figure 4-1 shows us the distribution of impacts for the processing stages. For the climate change category, the emissions from the second casting stage of the reduction are insignificant (less than 1% of total). The electrolysis step of the reduction stage, has the highest share of all processing stages. My assessment allocate a share of 27% of the total impact on climate change to this stage. It is a very energy intensive stage. The high share of coal in the Chinese electricity mix highly affects the results.

From my structural path analysis (SPA) of the global warming category, the largest and the 3rd largest path of impact found are related to the coal used for electricity production. Only these two paths, that both are related to the direct electricity demand, are responsible for *over 20%* of the total global warming potential (GWP) from the assessment. The assumption of the magnitude of the electricity demand for this process is therefore critical for the assessment.

China has an increasing hydropower capacity (Huang & Yan 2009), and the Inner Mongolia Region has a potential of both hydropower and wind power development (Martinot 2010). A shift towards renewable energy consumption in the Baotou processing plant will therefore significantly improve the environmental performance related to climate change of the neodymium production. However, coal power plants are still the major electricity producers in Inner Mongolia, so the assumption of the Chinese electricity mix seems reasonable.

Minor contributors to the high share from the electrolysis stage is the direct emissions from the electrolyte. The direct emissions are 4% of the total impact, where CO_2 and PFC has a share of 11% and 89% of respectively. I have assumed that the Hall-Héroult process is used for *neodymium reduction, electrolysis* and based the inventory data on aluminium production. The CO_2 emissions are a product of a reaction in the electrolyte when the carbon anodes are consumed. However, the major part of the global warming impact is from PFC emissions in the same process. During aluminium electrolysis the aluminium fluorides are used to lower the melting point in the electrolyte, and is a main source of these fluoride-related PFC emissions (European Commission 2001). If fluoride substances are used to facilitate adequate temperature conditions in the electrolyte in the Baotou processing plant is likely, but uncertain. An effort should be done to increase the insights of how the reduction of neodymium is performed to improve data quality, making it possible to make an inventory of the electrolysis with a higher reliability.

4.1.2.2 Advanced processing with high material inputs

The processing stage with the second highest share of GWP-related impact, is the extraction stage. The impact shares are 27%. Looking into the SPA, one finds that the fifth largest contributing path is the heavy fuel oil burned in the furnace (5 % of the total impacts). It represents 18% of the impacts at the extraction stage. There are few other large paths related to the extraction stage. By looking into the full length of the SPA, one can find that there are many small paths related to the extraction stage. They are mainly related to the sodium chloride, sulphuric acid and sodium hydroxide production. The largest stems from the energy processes, but also emissions during the chemical processing and transport of the materials. We conclude that the climate change impacts at this stage are mainly related to the high material input at this stage, where the production of these have substantial impacts.

Table 4-2 Comparisons of the shares of the processing stages of the direct electricity demand, direct energy demand and global warming impact for the production of neodymium metal

	SHARE OF DIRECT ELECTRICITY DEMAND	SHARE OF DIRECT ENERGY DEMAND	SHARE OF TOTAL GWP
NEODYMIUM REDUCTION, CASTING	0,09 %	0,7 %	0,3 %
NEODYMIUM REDUCTION, ELECTROLYSIS	70 %	28 %	27 %
SOLVENT EXTRACTION TO NEODYMIUM OXIDES	22 %	9 %	17 %
EXTRACTION OF BASTNÄSITE CONCENTRATE TO RE CHLORIDES	0,6 %	23 %	27 %
BENEFICIATION OF IRON ORE TO REO CONCENTRATE	8 %	3 %	20 %
MINING OPERATIONS	0,00 %	36 %	10 %

In table 4-2 we see the distributions of the global warming impact and energy demand for the processing stages. From the table we see that the beneficiation stage has a small direct energy demand. It does however have a higher share of the impacts related to climate change, with 20%, making it the 3rd largest of the processing stages. Equal to the extraction stage, the many small paths related to the upstream processing of input materials is important for understanding the contributions from this stage. Table 4-3 gives a picture of how this complex impact.

Table 4-3, Seven largest paths for the beneficiation stage found in the structural path analysis (SPA) in Arda for the production of neodymium metal. Ecoinvent process names are simplified.

Overall rank		***9***	***10***	***11***	***12***	***13***	***16***	***17***
Absolute [kg CO2 eq.]		**1,12**	**1,06**	**0,96**	**0,53**	**0,50**	**0,05**	**0,03**
Relative to total impact(%)		**2**	**2**	**1**	**1**	**1**	**0,08**	**0,04**
TIER	**4**	beneficiation	beneficiation	beneficiation	beneficiation	beneficiation	beneficiation	beneficiation
	5	sodium silicate	Chinese electricity mix	fatty alcohol	fatty alcohol	sodium carbonate	fatty alcohol	sodium carbonate
	6	heat from an industrial furnace	electricity generated from hard coal	n-olefins	n-olefins	liquid ammonia	n-olefins	
	7	natural gas burned in industrial furnace	hard coal burned in power plant	ethylene	heat from an industrial furnace	steam reforming of liquid ammonia		
	8				natural gas burned in industrial furnace			

17% of the impacts are related to the solvent extraction stage. The most important paths are related to the electricity production, since this stage has the second highest electricity consumption. Other paths are relatively small, the largest are related to the disposal of solvents mixture (3% of total impact) and ammonium bicarbonate (less than 1% of total impact). The mining stage is responsible 10% of the total impact, and most of this is related to the direct emissions during diesel consumption from the trucks at the mining site.

4.1.2.3 Consequences of European modelling of Chinese production

Table 4-4, 10 top processes in the climate change category supplied from the Arda software for the production of neodymium metal. Ecoinvent process names are simplified.

Process description	Rank	Absolute value [Co2 eq.]	Relative share
Hard coal burned in Chinese power plant	**1**	14,10	22 %
Hard coal at Chinese mine [to be supplied to power plant]	**2**	5,41	8 %
Diesel burned in mining trucks	**3**	4,71	7 %
Heavy fuel oil burned in industrial furnace	**4**	3,86	6 %
Natural gas burned in industrial furnace	**5**	3,41	5 %
Neodymium reduction, electrolysis	**6**	2,48	4 %
Disposal of solvents mixture	**7**	1,94	3 %
Lignite burned in German power plant	**8**	1,92	3 %
Ethylene (used in fatty alcohols)	**9**	1,49	2 %
Hard coal burned in German power plant	**10**	1,40	2 %

Amongst the top contributing process, displayed in table 4-4, we see that many of them are energy processes. The top two is related to our direct electricity demand – the coal power processes in China. Process 3 and 4, from diesel consumption in mining and heat energy demand in processing, are energy processes from the direct demand from the neodymium metal production. Number 5, *natural gas burned in industrial furnace,* is not directly from the constructed inventory. It is a result of the energy required during the production of chemical and other material inputs to the process. It is based on European technology, which is the cast for most processes available in the Ecoinvent database. It is important to consider whether the Chinese production would have the same share of natural gas used for heating the furnaces during production. It is well-known that China is reliant on heavier hydrocarbons like coal and heavy fuel oil for these kind of industrial energy processes.

Path 8 and 10 represents processes related to the German power production. Since most Ecoinvent processes are based on European technology, the electricity for production of material inputs is modelled from a (Continental) European electricity production mix. This mix has electricity supplied from several countries. We see that the impacts related to only the electricity share from German coal power generation ranks within the top ten processes. In fact, many of the top processes are related to dirty, coal-based power generation in various European countries. Figure 4-2 gives a better picture of the importance of these impacts related to the upstream electricity demand. The Chinese electricity mix have an even higher share of this type of dirty power generation. If the materials are produced with the Chinese electricity mix, the impacts from these processes are higher than I have found in this assessment.

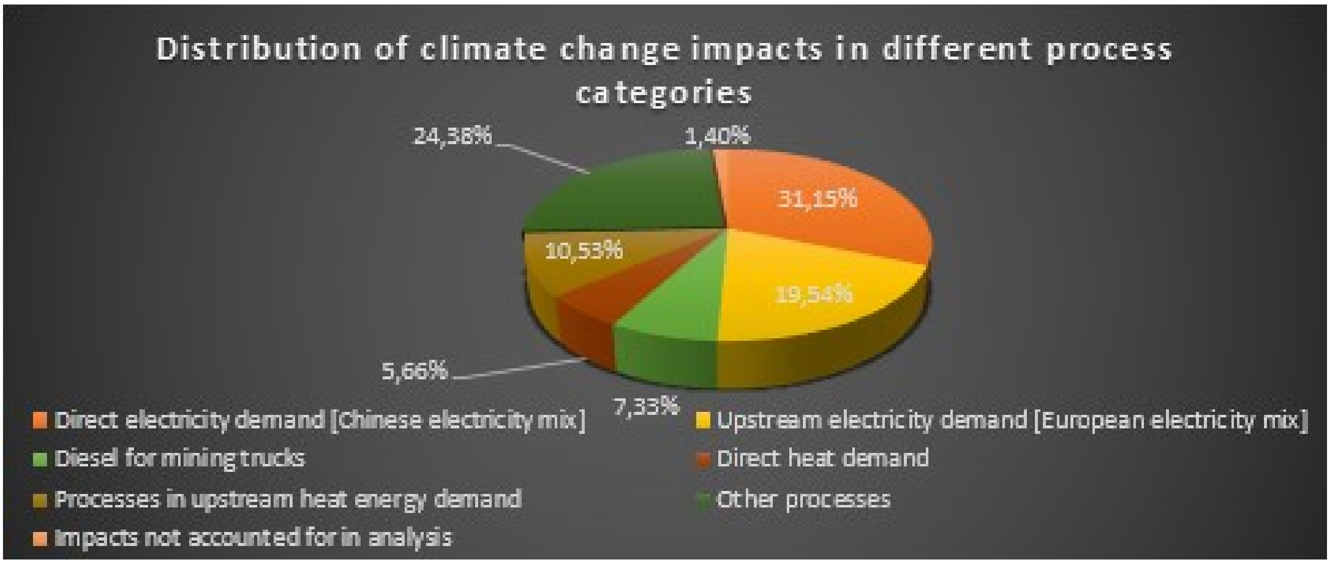

Figure 4-2, Distribution of climate change impacts sorted in convenient process categories for the production of neodymium metal. The figure is constructed of data from the analysis of the top processes for the climate change category.

4.1.3 Energy efficient operation

A simple sensitivity analysis was performed to investigate how a more energy efficient operation would affect the environmental impacts. From the background theory, we know that there is some uncertainty about the state of the Chinese RE industry (Sprecher et al. 2014; Schüler et al. 2011). As a simple review of the dependence of these processes, I assumed an average value of energy reduction for all industrial energy processes. The diesel used in mining is not included for the reduction analysis. In my inventory I have used three data values for energy requirements from the detailed report of Talens Peiró & Villalba Méndez (2013). From the range presented in their article, the average mean was used in the original inventory. However, by comparing these to the lower values in their range, an average reduction factor of 0,801 was established.

Table 4-5, Results from the sensitivity analysis the energy efficient operation for the production of neodymium metal

Category name	*Unit*	Adjusted impact	Original impact	Relative decrease
Climate change	*kg CO2 eq*	5,92E+01	6,42E+01	8 %
Fossil depletion	*kg oil eq*	1,69E+01	1,80E+01	6 %
Freshwater ecotoxicity	*kg 1,4-DB eq*	6,44E-01	6,57E-01	2 %
Freshwater eutrophication	*kg P eq*	2,26E-02	2,31E-02	2 %
Human toxicity	*kg 1,4-DB eq*	1,74E+02	1,75E+02	0,5 %
Marine ecotoxicity	*kg 1,4-DB eq*	6,34E+00	6,35E+00	0,3 %
Marine eutrophication	*kg N eq*	1,04E+00	1,04E+00	0,07 %
Metal depletion	*kg Fe eq*	1,44E+02	1,44E+02	0,01 %
Ozone depletion	*kg CFC-11 eq*	5,88E-06	5,99E-06	2 %
Particulate matter formation	*kg PM10 eq*	3,79E-01	3,92E-01	3 %
Photochemical oxidant formation	*kg NMVOC*	2,53E-01	2,71E-01	7 %
Terrestrial acidification	*kg SO2 eq*	4,61E-01	5,03E-01	8 %
Terrestrial ecotoxicity	*kg 1,4-DB eq*	8,49E-03	8,84E-03	4 %

Many of the categories are certainly always more coupled with the energy processes than others, but it is still interesting to see how the change in direct energy requirements affects the categories. An 8% decrease for climate impact confirms that a reduction in the direct energy requirements by 20% leads to a significant improvement. It is one of the most coupled categories. Still, we see that the reduction smaller than the reduction in direct energy use, thus energy saving actions alone will not dramatically mitigate emissions.

We see that the human toxicity and freshwater ecotoxicity categories is not affected that much by the reduction, meaning that for these categories the direct energy processes are of less importance for the order of the impact.

4.2 Production of NdFeB magnet

Table 4-6, Total impact from LCA of the production of 1 kg NdFeB magnet. Relative share of the impact from neodymium metal production in the right column.

Category name	Unit	Magnet results *Per kg NdFeB produced*	Relative share from Nd metal production
Climate change	kg CO2 eq	**2,83E+01**	67 %
Fossil depletion	kg oil eq	**7,14E+00**	75 %
Freshwater ecotoxicity	kg 1,4-DB eq	**2,42E-01**	81 %
Freshwater eutrophication	kg P eq	**8,35E-03**	82 %
Human toxicity	kg 1,4-DB eq	**5,39E+01**	96 %
Marine ecotoxicity	kg 1,4-DB eq	**1,93E+00**	98 %
Marine eutrophication	kg N eq	**3,10E-01**	100 %
Metal depletion	kg Fe eq	**4,36E+01**	98 %
Ozone depletion	kg CFC-11 eq	**1,85E-06**	96 %
Particulate matter formation	kg PM10 eq	**1,45E-01**	80 %
Photochemical oxidant formation	kg NMVOC	**1,18E-01**	68 %
Terrestrial acidification	kg SO2 eq	**2,36E-01**	63 %
Terrestrial ecotoxicity	kg 1,4-DB eq	**3,00E-03**	88 %

We see that for all categories the largest part of the impacts are related to the neodymium metal production. The categories with a low degree of coupling with energy processes have the highest share of neodymium metal-related impacts. Most of the inputs in the magnet part of the assessment are energy processes, and other processes than these affect the results to a low level.

The terrestrial acidification potential category (TAP) has the lowest share of Nd metal-related impacts, and is a category where the top processes responsible for the impact are energy-related. Other processes related to this category only has small impacts, like the nickel used in electroplating, which contributes 3%. For the human toxicity potential category (HTP), energy processes are less important. Here as well, the other processes from the magnet inventory only have small impacts. The 4th largest path in the SPA, disposal of sulphidic tailings, related to the nickel in the electroplating process, is responsible for less than 1% of the impact.

Table 4-7, Top 10 processes for the impact of the climate change category for 1 kg of NdFeB magnet produced. Includes the share of the process of the total global warming impact (middle column, 28,3 CO2 eq.). The relative share of impact from the process related to the neodymium metal production is also included (right column). The process names are simplified.

Process name	Rank	Relative share of total global warming impact	Relative share of process impact from Nd metal production
Hard coal burned in Chinese power plant	**1**	35 %	42 %
Hard coal at Chinese mine [to be supplied to power plant]	**2**	13 %	42 %
Diesel burned in mining trucks	**3**	5 %	98 %
Heavy fuel oil burned in industrial furnace	**4**	4 %	99 %
Natural gas burned in industrial furnace	**5**	4 %	98 %
Neodymium reduction, electrolysis	**6**	3 %	100 %
Disposal of solvents mixture	**7**	2 %	100 %
Lignite burned in German power plant	**8**	2 %	96 %
Ethylene (used in fatty alcohols)	**9**	2 %	100 %
Hard coal burned in German power plant	**10**	2 %	96 %

From table 4-7 we see that it is the same processes are dominating the climate change category as it was for the neodymium metal production. The magnet production lead to a substantial increase in the direct electricity demand. We see that the impacts related to local (Chinese) electricity production has a higher share connected to the magnet production. During the magnet production there are less materials input, thus the other processes has high share related to the neodymium metal production. Most of the process show a share of 94-98% from the Nd metal production. It is interesting to see how little the iron (and boron) processing affects the results compared to the neodymium metal. The natural gas and European electricity mix are a parts of the inventory for the iron used, but does not have high shares of the impacts for processes like the natural gas (number 5) or German coal power plants (number 8 and 10). The largest impact connected to transportation is for lorry transport (rank 14), and have a share of 75% related to the neodymium metal production, being of among the lowest shares of this assessment.

4.3 Production of electricity from offshore DD-PMG wind turbines

Table 4-8, Total impact from the hybrid life cycle assessment of 1 kWh from wind power electricity from offshore DD-PMG turbines, including the relative impact from the monetary IO subsystem.

RESULTS FROM HYBRID LCA OF 1 KWH OF ELECTRICITY

Impact category, unit	**Total impact, DD-PMG**	**Relative impact from IO subsystem**
Climate change, kg CO2 eq	**3,36E-02**	53 %
Fossil depletion,kg oil eq	**4,73E-03**	0,00 %
Freshwater ecotoxicity,kg 1,4-DB eq	**4,07E-04**	0,02 %
Freshwater eutrophication, kg P eq	**1,13E-05**	0,00 %
Human toxicity, kg 1,4-DB eq	**2,01E-02**	4,4 %
Marine ecotoxicity, kg 1,4-DB eq	**4,47E-04**	0,8 %
Marine eutrophication, kg N eq	**1,54E-05**	34 %
Metal depletion, kg Fe eq	**1,18E-02**	0,00 %
Ozone depletion, kg CFC-11 eq	**1,21E-09**	0,00 %
Particulate matter formation, kg PM10 eq	**7,03E-05**	27 %
Photochemical oxidant formation, kg NMVOC	**1,55E-04**	39 %
Terrestrial acidification, kg SO2 eq	**1,82E-04**	45 %
Terrestrial ecotoxicity, kg 1,4-DB eq	**2,49E-06**	18 %

The results from the assessment for the 15 applied impact categories are shown in table 4-8. We see contributions from the monetary IO subsystem in 9 of the categories. For the climate change category this represent over half of the total impact. We notice the other five categories where the IO-related impact is an important part of the contributions, marked with red. We also notice the four categories where there is no environmental extended IO tables in the EXIOPOL project, thus there is no impact from the IO subsystem.

Table 4-9, Total impact of hybrid life cycle analysis of 1 kWh from wind power electricity from offshore conventional turbines, including the relative impact from the monetary IO sub system and the relative change in impact from the conventional to the DD-PMG technology results

RESULTS FROM HYBRID LCA OF 1 KWH OF ELECTRICITY

Impact category, unit	**Total impact, conventional**	**Relative impact from IO part**	**Relative change from conventional to DD-PMG**
Climate change, kg CO2 eq	*3,51E-02*	52 %	96 %
Fossil depletion,kg oil eq	*5,03E-03*	0,00 %	94 %
Freshwater ecotoxicity,kg 1,4-DB eq	*5,25E-04*	0,02 %	77 %
Freshwater eutrophication, kg P eq	*1,31E-05*	0,00 %	86 %
Human toxicity, kg 1,4-DB eq	*2,33E-02*	4 %	86 %
Marine ecotoxicity, kg 1,4-DB eq	*5,47E-04*	0,7 %	82 %
Marine eutrophication, kg N eq	*1,18E-05*	46 %	130 %
Metal depletion, kg Fe eq	*1,47E-02*	0,00 %	81 %
Ozone depletion, kg CFC-11 eq	*1,27E-09*	0,00 %	95 %
Particulate matter formation, kg PM10 eq	*7,56E-05*	26 %	93 %
Photochemical oxidant formation, kg NMVOC	*1,62E-04*	38 %	96 %
Terrestrial acidification, kg SO2 eq	*1,91E-04*	44 %	95 %
Terrestrial ecotoxicity, kg 1,4-DB eq	*2,82E-06*	16 %	88 %

From table 4-9 above we clarify that the results for the conventional investigated is equal to the turbine investigated by Arvesen et al. (2013). Because of further developments of the Ecoinvent database and Recipe framework since publication of the article, the impact for fossil depletion (-6%), freshwater ecotoxicity (+24%), marine ecotoxicity (+20%), marine eutrophication (-137%) and metal depletion (+16%) has changed significantly from the values that appear in Arvesen et al. (2013).

From the relative values with the DD-PMG turbine, we see that the DD-PMG turbine generally has a better environmental performance than the conventional turbine. In my analysis, only in the marine eutrophication category the impact from the new technological solution is higher. The toxicity categories are the categories where we see the highest reductions, together with freshwater eutrophication and metal depletion.

Table 4-10, Impact related to the physical process-based part of the assessment for the DD-PMG and conventional turbine technology, including the relative change in impact from the conventional to the DD-PMG system.

RESULTS FROM PROCESS LCA OF 1 KWH OF ELECTRICITY

Impact category, unit	**Impact, DD-PMG**	**Impact, conventional**	**Relative change from conventional to DD-PMG**
Climate change, kg CO2 eq	**1,58E-02**	*1,68E-02*	94 %
Fossil depletion,kg oil eq	**4,73E-03**	*5,03E-03*	94 %
Freshwater ecotoxicity,kg 1,4-DB eq	**4,07E-04**	*5,25E-04*	77 %
Freshwater eutrophication, kg P eq	**1,13E-05**	*1,31E-05*	86 %
Human toxicity, kg 1,4-DB eq	**1,92E-02**	*2,24E-02*	86 %
Marine ecotoxicity, kg 1,4-DB eq	**4,43E-04**	*5,44E-04*	81 %
Marine eutrophication, kg N eq	**1,01E-05**	*6,43E-06*	158 %
Metal depletion, kg Fe eq	**1,18E-02**	*1,47E-02*	81 %
Ozone depletion, kg CFC-11 eq	**1,21E-09**	*1,27E-09*	95 %
Particulate matter formation, kg PM10 eq	**5,11E-05**	*5,59E-05*	91 %
Photochemical oxidant formation, kg NMVOC	**9,48E-05**	*9,97E-05*	95 %
Terrestrial acidification, kg SO2 eq	**1,01E-04**	*1,08E-04*	94 %
Terrestrial ecotoxicity, kg 1,4-DB eq	**2,05E-06**	*2,37E-06*	86 %

From table 4-10, we see that when we are considering the pure process part of the LCA, the relative changes amplifies compared to table 4-9. The results from table 4-10 will be further discussed in the rest of the discussion.

4.3.1 Importance of the increase in annual energy yield

Increasing the electricity power production is one of the key economic drivers of the technological development of wind turbines, and is well known as a cost-effective action of improving the environmental performance. Figure 4-3 below show all relative reductions in the DD-PMG system, where the percentage points of reduction related to the energy production increase is displayed separately from the other reductions of the system.

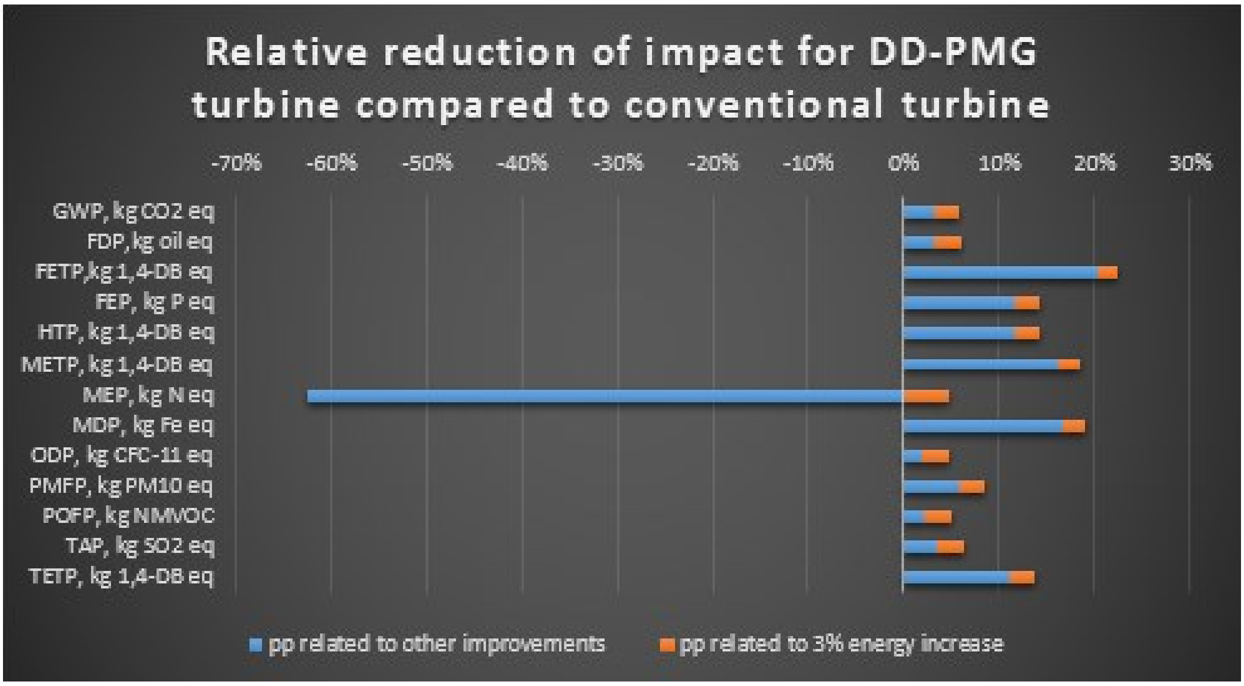

Figure 4-3, Relative reduction of impact for DD-PMG turbine compared to the conventional turbine. The reductions that were not related to an increase in the electricity production was found, and are represented in the blue bars in the graph. The red bar represents the reductions related to the increase in electricity production. The total reductions for the categories are the sum of the two bars, except for the MEP category that has negative reductions (i.e. increases in impact) for the "other improvements" bar.

In figure 4-3 we still see that for most categories there are other parts of the inventory that are responsible for the reductions in impact for the DD-PMG turbine. However, the global warming category is one important category where the increase in energy production is important for the decrease in environmental impact. 48% of total the reduction is because of the annual energy increase. Also for the other categories having lower reductions in the impact, these being the FDP, ODP, POFP and TAP categories, the energy production increase is important, and is responsible for more than 40% of the total reductions in impact. For the marine eutrophication category, the improvements because of the energy production increase conceal parts of an even larger increase in the environmental burden in the DD-PMG system.

4.3.2 The importance of the use of permanent magnet material in the system

Table 4-11, Relative shares of the NdFeB production for the production of electricity from wind power. The impact is divided between the production of neodymium metal (middle column) and the production of NdFeB magnets.

Relative share of the NdFeB-production			
Category name, unit	***Nd metal production***	***NdFeB production***	**All NdFeB**
Climate change, kg CO2 eq	*2 %*	0,8 %	***3 %***
Fossil depletion,kg oil eq	*2 %*	0,5 %	***2 %***
Freshwater ecotoxicity	*0,7 %*	0,2 %	***0,8 %***
Freshwater eutrophication, kg P eq	*0,8 %*	0,2 %	***1 %***
Human toxicity, kg 1,4-DB eq	*3 %*	0,2 %	***4 %***
Marine ecotoxicity, kg 1,4-DB eq	*6 %*	0,2 %	***6 %***
Marine eutrophication, kg N eq	*41 %*	0,2 %	***41 %***
Metal depletion, kg Fe eq	*5 %*	0,1 %	***5 %***
Ozone depletion, kg CFC-11 eq	*2 %*	0,1 %	***2 %***
Particulate matter formation, kg PM10 eq	*3 %*	0,8 %	***4 %***
Photochemical oxidant formation, kg NMVOC	*1 %*	0,6 %	***2 %***
Terrestrial acidification, kg SO2 eq	*2 %*	1 %	***3 %***
Terrestrial ecotoxicity, kg 1,4-DB eq	*2 %*	0,3 %	***2 %***

From the table 4-11, we observe that the impact from the production of NdFeB magnet material used in the turbine is quite modest for all categories. The exception is in the marine eutrophication category. Still, the impacts are considerable, taking into consideration that the PM material is an infinitesimal part of the system. The mass of the NdFeB magnet is only 0,46% of the total weight of the mill construction, leaving out foundation (substructures). In addition to the mill construction comes the impacts from other parts of the whole windmill park system, implying that the impacts from the NdFeB indeed are considerate.

For the global warming category, the relative NdFeB-impact is 2-3% of the process part of the assessment. The DD-PM generator is 2,46 times heavier, thus we see that the total generator impact is 6,46% versus 1,78% for the conventional turbine in this category. Still, by comparing the DD-PM generator to a conventional generator with the same weight, the new DD-PM generator increases the related GWP-impacts by about 38%. The permanent magnet mass corresponds to only 3,62% of the total generator weight. For the ozone depletion and fossil depletion categories the increase in impact would be 32% compared to an equally heavy conventional turbine.

Table 4-12, Relative share of the generator impact for the production of electricity from wind power, including the share of the generator impact that is related to NdFeB-production.

Category name, unit	Generator impact (relative)	NdFeB relative share of the generator impact
Climate change, kg CO2 eq	6 %	38 %
Fossil depletion,kg oil eq	6 %	33 %
Freshwater ecotoxicity,kg 1,4-DB eq	18 %	5 %
Freshwater eutrophication, kg P eq	18 %	6 %
Human toxicity, kg 1,4-DB eq	23 %	17 %
Marine ecotoxicity, kg 1,4-DB eq	22 %	27 %
Marine eutrophication, kg N eq	44 %	94 %
Metal depletion, kg Fe eq	21 %	23 %
Ozone depletion, kg CFC-11 eq	5 %	46 %
Particulate matter formation, kg PM10 eq	10 %	37 %
Photochemical oxidant formation, kg NMVOC	5 %	35 %
Terrestrial acidification, kg SO2 eq	9 %	37 %
Terrestrial ecotoxicity, kg 1,4-DB eq	13 %	16 %

The only category where the production of NdFeB magnets are truly dominating is the marine eutrophication category. The production is responsible for over 40% of the impact in our assessment, with the generator-related impacts being 6,6 times larger than the hypothetical equally heavy conventional counterpart. The emissions of ammonia from the solvent extraction stage during the processing of the rare earth concentrate is the main contributor. From the SPA, one can find that the two paths in question are the NdFeB magnet in the generator (25% of the impact), together with the NdFeB magnet content in the replacements of large parts (15%). There is reason to believe that the lifetime of a permanent magnet exceeds 25 years, so there is some uncertainty concerning the need for replacement of the NdFeB magnet. Nonetheless, my analysis shows high increases because of this production for the marine eutrophication category.

4.3.3 The importance of the use of copper in the system

The NdFeB share of the total impacts in the toxicity categories are various, with the freshwater ecotoxicity ranging lowest and the marine ecotoxicity showing the second highest impact share in table 4-11. Human toxicity has a medium high impact, with the NdFeB share being 4%. Table 4-12 indicate that for 6 categories, the four toxicity categories in addition to the freshwater eutrophication and metal depletion category, the NdFeB-related impacts are small compared to other parts of the generator. This section will investigate five of these categories: FETP, FEP, HTP, METP and TETP, which will be referred to as "the toxicity category group".

Table 4-13, Analysis of the top 50 structural path for selected impact categories for the impact of the production of electricity from wind power. The paths related to copper were grouped together. The copper share of the impact covered by the analysis is displayed in the far right column.

	Copper-related paths	Relative share of total impact covered	Copper share of covered impact
Freshwater ecotoxicity,kg 1,4-DB eq	27	69 %	59 %
Freshwater eutrophication, kg P eq	29	59 %	77 %
Human toxicity, kg 1,4-DB eq	34	69 %	80 %
Marine ecotoxicity, kg 1,4-DB eq	30	66 %	59 %
Terrestrial ecotoxicity, kg 1,4-DB eq	16	60 %	37%

For the HTP category, the copper consumption is dominating the impact. The disposal of the sulphidic tailings related to copper concentrate beneficiation is the most dominant process (53%), with the emissions from the copper refining process being the second largest (11%). Manganese (49% of total) and arsenic (20%) are the main stressors in question. The copper used in the (larger) DD-PM generator responsible for the major part of the generator-related impact, which is 23% of the total human toxicity impact.

Table 4-13 also indicate this fact. The top path for HTP in the conventional and DD-PMG turbine is related to the sulphidic tailings, stemming from the beneficiation of primary copper, which is used in the subsea external cabling in the wind farm system. The similar path related to the copper used in generator is the second highest for the conventional turbine (5%, 1,56 g CO_2-eq.), but is ranking 6th for the current DD-PMG design (3%, 0,6 g CO_2-eq.). There is less copper in the DD-PM generator, only 58% of conventional copper mass, and this reduction is a main driver for the decrease in impact for the HTP category.

Tables 4-12 clarifies this. The data is from a part of a sensitivity analysis, where the copper in the generator is more than doubled, from 6,0 tons to 12,8 tons. The amount of NdFeB material is unchanged. We see that the impact increases significantly in the toxicity category group compared to the reference scenario.

Table 4-14, Results for impacts from a high copper share scenario of the production of electricity from wind power using DD-PMGs. Comparisons of the high copper scenario with the reference scenario of the DD-PMG system and of the high copper scenario with the conventional turbine system are included.

Impact category, unit	***High copper scenario impact***	***Change from reference scenario***	***Change from conventional design***
Climate change, kg CO2 eq	**1,59E-02**	+0,1 %	*-5,8 %*
Fossil depletion,kg oil eq	**4,73E-03**	+0,1 %	*-6,0 %*
Freshwater ecotoxicity,kg 1,4-DB eq	**4,62E-04**	+3,6 %	*-12 %*
Freshwater eutrophication, kg P eq	**1,29E-05**	+4,7 %	*-1,6 %*
Human toxicity, kg 1,4-DB eq	**2,28E-02**	+8,3 %	*+1,5 %*
Marine ecotoxicity, kg 1,4-DB eq	**5,01E-04**	+3,2 %	*-7,8 %*
Marine eutrophication, kg N eq	**1,03E-05**	+1,4 %	*+60 %*
Metal depletion, kg Fe eq	**1,28E-02**	+7,9 %	*-13 %*
Ozone depletion, kg CFC-11 eq	**1,21E-09**	+0,3 %	*-4,5 %*
Particulate matter formation, kg PM10 eq	**5,24E-05**	+2,5 %	*-6,3 %*
Photochemical oxidant formation, kg NMVOC	**9,57E-05**	+1,0 %	*-4,0 %*
Terrestrial acidification, kg SO2 eq	**1,05E-04**	+3,7 %	*-2,9 %*
Terrestrial ecotoxicity, kg 1,4-DB eq	**2,20E-06**	+7,7 %	*-7,1 %*

An important point is, by comparing the high copper scenario and the conventional design, we find that the increase in copper mass in the generator, from 10,4 tons in the conventional design to 12,8 tons in this alternative scenario, gives a total increase in HTP impact. The somewhat small increase in copper mass is more important than the large total mass reductions for the generators, confirming the importance of the copper use for the HTP category in particular. For terrestrial ecotoxicity, the importance of the assumption of the copper share in the generator is smaller. However, for all the 5 discussed categories, we see how the assumption of the copper share affects the environmental performance.

Similar to HTP, the FEP, FETP and METP have the top path related to the sulphidic tailings from the copper in the external cablings. The similar path related to the copper in the generator ranks from number 5-7.

For the METP, the top path related to the generator stems from the processing of rare earths. It is from the mentioned cobalt emissions during the extraction stage, ranking as the 4th largest path (3% of the impact). From table 4-11, we know that this is the category in the toxicity category group where the impact from NdFeB has the highest relevance.

4.3.4 Importance of other metal processes because of mass reductions in generator

In general, other impacts for the toxicity category group mainly stem from other metal extraction processes for manufacturing the turbine. Some of the impact stems from energy processes, like the impact from spoil from lignite and coal mining. For the TETP, these processes are more important than the copper processing (table 4-13). Metal extraction of steel and iron cover 41% of the top 50 paths. Impacts related to the operation of marine vessels are important paths in this category and related paths are responsible for 16% of the covered impact. The impacts are related to fuel extraction or direct emissions from vessel operation.

Table 4-14 effectively points out the categories where the copper does not affect the results in the same degree. The marine eutrophication, ozone depletion, photochemical oxidant formation, fossil depletion and climate change categories show only small changes when increasing the copper share. From figure 4-3 we also recognise the last four categories as categories where a high share of the reductions are related to the annual energy production increase. These are also the categories with the lowest overall reductions (table 4-10).

By firstly investigating the climate change category, we can find interesting explanations for the overall reductions in impact for these categories. From the table 4-15 we see that, similar to the results in Arvesen et al. (2013), the operation of marine vessels has a considerably high impact. Metal-related processes are also an important part of the picture, for example related to the pig iron, clinker and iron sintering.

Comparing with the results from the conventional turbine, it is evident that the results are similar, but that many processes have higher impact for the conventional turbine (table 4-15). The smallest reductions in the table are related to the electricity power production increase, e.g. for almost all of the decrease related to the marine vessel operations.

Much of reduction in the global warming potential impact are related to the mass savings in the DD-PM generator versus the conventional generator and gearbox system. The DD-PM generator has an impact of 1,02 g CO2-eq, which is less than 1,46 g CO2-eq. from the conventional generator and gearbox system. This represents 77% of the reductions in impacts that is not related to the energy production increase. The higher reductions seen for the natural gas burned in industrial furnace and the hard coal burned in industrial furnace in table 4-15 are related to the decrease of the chromium steel in the DD-PMG design. Higher quality steel, here approximated as chromium steel, is modelled as a part of the gearbox for the conventional design.

In addition, we have a higher compactness in the DD-PMG nacelle. These mass savings in the other components of the nacelle lead to reductions for top processes like *pig iron* and *glass-filled nylon* and *iron sintering.* There is also some chromium steel used in the main shaft.

The coal from Chinese power production is responsible for around 1% of the climate change potential impact. This is related to the electricity consumption during the production of neodymium metal in the Baotou processing plant.

Table 4-15, Top processes for the climate change category displaying their absolute impact and relative impact of the production of electricity from wind power using DD-PMGs. The relative impact compared to the conventional turbine impact is also shown. Ecoinvent process names are simplified. The top two processes are categorised. The operation of marine vessels is merged of the operation of barges and transoceanic freight ships. All processes from the European fossil power production are merged together.

Rank	**Process**	**Absolute impact [CO2-eq.]**	**Relative values of total impact**	**Relative to conventional turbine impact**	**Conventional turbine rank**
1	Operation of marine vessels	3,75E-03	24 %	97 %	**1**
2	Fossil power production, Europe	2,27E-03	14 %	77 %	**2**
3	Pig iron	1,92E-03	12 %	94 %	**3**
4	Glass-filled nylon	1,75E-03	11 %	96 %	**4**
5	Clinker	9,33E-04	6 %	97 %	**5**
6	Natural gas burned in industrial furnace	6,37E-04	4 %	86 %	**6**
7	Iron sintering	4,84E-04	3 %	94 %	**8**
8	Hard coal burned in industrial furnace	3,85E-04	2 %	58 %	**7**
9	Quicklime in pieces	2,79E-04	2 %	93 %	**9**
10	Lorry operation	2,01E-04	1 %	97 %	**10**
11	Diesel from mining trucks	1,96E-04	1 %	99 %	**11**
12	Refinery gas burned during diesel refining	1,68E-04	1 %	98 %	**12**
13	Hard coal burned in Chinese power production	1,35E-04	0,9 %	-	**-**
14	Heavy fuel oil burned in industrial furnace	1,22E-04	0,8 %	90 %	**13**

Going into detail for the ODP and POFP categories, we discover similar findings as in the climate change category. From the results in the ODP category, we find that the energy requirements from steel production are important for the reductions. Fossil fuel extraction process related to vessel operations and energy use during material processing dominate the category. The decrease in processes like *natural gas transport* are related to the chromium steel. The chromium steel mass reductions are 65% from the conventional to the DD-PMG turbine. Other mass reductions, as the glass fibre in the cover of the nacelle, lead to minor reductions in impact from some chemical processes. Impact from the larger glass fibre masses in the rotor, which is equal for the two designs, are larger and important for the total impact.

The PMFP and TAP categories range between the group with the toxicity categories and the group with FEP, GWP, ODP and POFP. They have similar shares of the reductions that are related to the energy production increase (figure 4-3), and reductions are affected by both the reduction in copper use and other mass reductions in the nacelle, like chromium steel. In the PMFP we have significant reductions in copper-related processes. Reductions in processes like *high-carbon ferrochromium* by 49 % and *ferronickel* by 44%, related to the chromium steel, also contribute to the total reduction in this category. In addition, already discussed processes like hard coal burned in industrial and glass-filled nylon have small contribution to these reduction.

For the TAP category, the impact mainly stem from vessel operations and metal processing. This is similar to the impact from the PMFP category, and the reductions follow a similar pattern.

4.3.5 Scenario analysis

From table 3-24, we see that the moderate scenario includes a decrease in downtime relative to the reference scenario. The reduced downtime gives a general decrease in impact by approximately 1 pp in all categories. The logic behind the assumptions for this scenario is that the generator failures leads to high downtimes, in opposition to converter failures. Thus, the overall downtime decreases. However, in this scenario, it is assumed that the maintenance operations will even out for the converter versus gearbox failures. We see that this realistic scenario will lead to reductions in the impacts proportional to the increased availability of the turbine. By further investigations we find the increased replacement rate only have small significance for the impact, which is under 0,01 pp for all categories. A much larger increase than 2,5% for the replacement of small parts for the DD-PMG turbine must be the case to significantly affect the environmental impact. This seems unlikely.

However, an actual maintenance increase in the moderate scenario will lead to significant changes for some of the categories. A 7% increase in operational maintenance will for these categories even out a potential decrease in the downtime of the turbine. The moderate scenario including the maintenance increase shows reductions in most categories compared to the reference scenario, albeit incremental for some of them, but also a net increase in impact for the ozone depletion and photochemical oxidant formation categories. The difference between the moderate and the moderate-optimistic scenario effectively shows us how a 7% maintenance decrease will affect the ecological impact. We understand that the use of marine vessels in maintenance operations is as important as changes in the downtime for fossil-sensitive categories like GWP, FDP, ODP, POFP and TAP.

There is uncertainty around the need for maintenance for the new DD-PMG turbine, and the optimistic scenario reflects the optimists in the wind power industry. The scenario represents a large (32%) decrease in operational maintenance. The optimistic reductions found in this scenario can be reached as the technology matures. A large decrease in the operational maintenance will indeed lead to significant improvements for some of the categories, underlining the findings in the paragraph above. Again, the fossil fuel-sensitive categories show reductions by 3-6 pp due to the maintenance decrease alone. As the reductions in impact for these categories is due to the reduction in vessel operations, it elaborates the importance to reduce the maintenance operations at offshore site to reduce the environmental impact of offshore wind power. A potential maintenance decrease may be an important benefit of the DD-PMG turbine technology.

Reductions seen in categories like freshwater eutrophication, freshwater and marine ecotoxicity, human toxicity and metal depletion are mostly because of the decrease in downtime for the optimistic scenario. Leaving out these reductions, and only considering the optimistic decrease in operational maintenance, we see that the marine eutrophication (2 pp), particulate matter formation (2-3 pp) and terrestrial acidification categories (2 pp) show moderate reductions for this scenario.

In all categories, except the MEP, the pessimistic scenario shows lower impacts than the conventional turbine.

Table 4-16, Impact of the production of electricity from wind power using DD-PMGs for each of the scenarios presented in section 3.5.2.6. Relative difference compared to the reference scenario is indicated below the absolute values of impact for every category.

Category name, unit	***Optimistic***	***Moderate-optimistic***	***Moderate***	***Moderate, maintenance increase***	***Moderate-pessimistic***	***Pessimistic***
Climate change, kg CO2 eq	1,50E-02	1,55E-02	1,57E-02	1,58E-02	1,60E-02	1,63E-02
	-6 %	*-2 %*	*-1 %*	*-0,2 %*	*1 %*	*3 %*
Fossil depletion,kg oil eq	4,45E-03	4,64E-03	4,68E-03	4,73E-03	4,78E-03	4,87E-03
	-6 %	*-2 %*	*-1 %*	*-0,08 %*	*1 %*	*3 %*
Freshwater ecotoxicity,kg 1,4-DB eq	3,99E-04	4,02E-04	4,03E-04	4,03E-04	4,07E-04	4,12E-04
	-2 %	*-1 %*	*-1 %*	*-1 %*	*0,08 %*	*1 %*
Freshwater eutrophication, kg P eq	1,10E-05	1,11E-05	1,11E-05	1,12E-05	1,13E-05	1,14E-05
	-2 %	*-1 %*	*-1 %*	*-1 %*	*0,1 %*	*1 %*
Human toxicity, kg 1,4-DB eq	1,89E-02	1,90E-02	1,90E-02	1,91E-02	1,93E-02	1,95E-02
	-2 %	*-1 %*	*-1 %*	*-1 %*	*0,07 %*	*1 %*
Marine ecotoxicity, kg 1,4-DB eq	4,35E-04	4,38E-04	4,39E-04	4,39E-04	4,43E-04	4,49E-04
	-2 %	*-1 %*	*-1 %*	*-0,9 %*	*0,09 %*	*1 %*
Marine eutrophication, kg N eq	9,74E-06	9,98E-06	1,00E-05	1,01E-05	1,02E-05	1,04E-05
	-4 %	*-2 %*	*-1 %*	*-0,5 %*	*0,5 %*	*2 %*
Metal depletion, kg Fe eq	1,17E-02	1,17E-02	1,17E-02	1,17E-02	1,19E-02	1,20E-02
	-2 %	*-1 %*	*-1 %*	*-1 %*	*0,03 %*	*1 %*
Ozone depletion, kg CFC-11 eq	1,11E-09	1,18E-09	1,19E-09	1,21E-09	1,22E-09	1,25E-09
	-8 %	*-2 %*	*-1 %*	*0,3 %*	*1 %*	*4 %*
Particulate matter formation, kg PM10 eq	4,86E-05	5,02E-05	5,06E-05	5,09E-05	5,15E-05	5,24E-05
	-5 %	*-2 %*	*-1 %*	*-0,3 %*	*0,7 %*	*3 %*
Photochemical oxidant formation, kg NMVOC	8,69E-05	9,24E-05	9,38E-05	9,52E-05	9,62E-05	9,87E-05
	-8,35 %	*-2,53 %*	*-1,03 %*	*0,47 %*	*1,52 %*	*4 %*
Terrestrial acidification, kg SO2 eq	9,48E-05	9,87E-05	9,97E-05	1,01E-04	1,02E-04	1,04E-04
	-6 %	*-2 %*	*-1 %*	*-0,07 %*	*1 %*	*3 %*
Terrestrial ecotoxicity, kg 1,4-DB eq	1,96E-06	2,01E-06	2,02E-06	2,04E-06	2,06E-06	2,09E-06
	-4 %	*-2 %*	*-1 %*	*-0,5 %*	*0,6 %*	*2 %*

4.4 Reliability of the results

4.4.1 Reliability for the production of electricity from offshore DD-PMG wind turbines

From a literature review of LCAs of wind power, it is suggested that the average carbon footprint from the offshore segment to be in the range of 9-22 g CO2 eq./ kWh (12 g CO2/kWh average) (Arvesen & Hertwich 2012). The found value in the hybrid assessment of 33,6 g CO2/kWh is therefore higher than the estimated range, comparing with another hybrid analysis of 33,4 g CO2 (Wiedmann et al. 2011). The process study of Wagner et al. (2011) also has similar results (32,0 CO2 eq. /kWh). However, most of the investigated assessments in Arvesen & Hertwich (2012) are process LCAs, and we see that the process part of the current study (with 15,8 g CO2/kWh) is within the suggested range. As pointed out in Arvesen & Hertwich (2012) the results from wind power LCAs varies because of the wide range of systems studied, key assumptions taken and difference in methods used.

Another simple sensitivity analysis was performed, where an increased mass of copper replaced all the NdFeB in the generator. From table 4-17 we see the results, where there are increases in the toxicity category group. The results underline the fact that for this group the current inventory may not cover the complete picture of the REE production. Both copper and REEs are metals that are found in low ore grades and require advanced and complex processing. The results for them are expected to be similar. There are still large uncertainties regarding the current state of the Chinese REE industry, and it is challenging to find hard (empirical) data for this part of the inventory. A further discussion of this follows in section 4.4.3.

Table 4-17, Comparative results from sensitivity analysis where the reference scenario turbine is changed to a turbine where all NdFeB is replaced by additional copper. The change of the impact of the production of electricity from wind power from the reference scenario to the no-NdFeB scenario is shown in the right column.

IMPACT CATEGORY, UNIT	CHANGE FROM REFERENCE SCENARIO
CLIMATE CHANGE, KG CO2 EQ	98 %
FOSSIL DEPLETION,KG OIL EQ	98 %
FRESHWATER ECOTOXICITY,KG 1,4-DB EQ	105 %
FRESHWATER EUTROPHICATION, KG P EQ	106 %
HUMAN TOXICITY, KG 1,4-DB EQ	104 %
MARINE ECOTOXICITY, KG 1,4-DB EQ	100 %
MARINE EUTROPHICATION, KG N EQ	59 %
METAL DEPLETION, KG FE EQ	99 %
OZONE DEPLETION, KG CFC-11 EQ	98 %
PARTICULATE MATTER FORMATION, KG PM10 EQ	97 %
PHOTOCHEMICAL OXIDANT FORMATION, KG NMVOC	99 %
TERRESTRIAL ACIDIFICATION, KG SO2 EQ	99 %
TERRESTRIAL ECOTOXICITY, KG 1,4-DB EQ	102 %

For energy-dependent categories like climate change, it seems like the current inventory is satisfactory. The individual separation of the elements of the rare earths is energy consuming, and it seems likely that the NdFeB should have a higher carbon footprint that the copper-related

Ecoinvent process. It seems like the high material and energy consumption during processing gives expected environmental impacts. Keep in mind that the reductions seen in the marine eutrophication category is because the omission of the ammonia-emissions related to the neodymium magnet production.

Through the sensitivity analysis performed in section 4.4.3, where the copper mass was increased, we understood the importance of the copper mass assumption. The lower copper mass assumption in the reference scenario is credible. Although, as mentioned in the inventory (section 3.5.2), there is a range of acceptable values for the NdFeB and copper share that will cause some changes in the results.

There is a possibility that the copper mass in the generator of the conventional turbine is in the higher range of published data. Data from personal communication with an expert on power engineering indicates lower copper shares in the generator. Kabir et al. (2012) and Dones et al. (2007) present the same in the data from their studies. A potential (large) decrease of the copper mass in the conventional turbine will greatly affect the comparison with presented in the discussion section.

The value of annual energy increase is also important for the overall performance, and although the value seem credible, the exact value will vary upon factors like local meteorology and exact windmill configurations.

4.4.2 Comparisons of the results of the NdFeB magnet

Table 4-18, Comparisons of results from Sprecher (2014) to the some of the results for the NdFeB magnet in section 4.2. Methods and framework used are different, and should be considered with a grain of salt.

Sprecher (2014)			Current study in similar categories	
Category name	**Results for 1 kg NdFeB magnet (HDD app.)**	**Units**	**Results for 1 kg NdFeB magnet (wind turbine app.)**	**Units**
eutrophication potential, average European[RER]	1,89E-01	kg NOx-Eq		
acidification potential, average European[RER]	4,41E-01	kg SO2-Eq	2,36E-01	kg SO2 eq
photochemical oxidation (summer smog), high NOx POCP[RER]	1,72E-02	kg ethylene-Eq		
climate change, GWP 100a[GLO]	2,65E+01	kg CO2-Eq	2,83E+01	kg CO2 eq
ionising radiation, ionising radiation[GLO]	5,11E-08	DALYs		
freshwater aquatic ecotoxicity, FAETP infinite[GLO]	1,39E+01	kg 1,4-DCB-Eq	1,95E-01	kg 1,4-DB eq
stratospheric ozone depletion, ODP steady state[GLO]	2,59E-06	kg CFC-11-Eq		
human toxicity, HTP infinite[GLO]	1,49E+02	kg 1,4-DCB-Eq	5,39E+01	kg 1,4-DB eq

From table 4-18 we conclude that there is consistency seen for the results in the climate change category. However, the life cycle assessment by Sprecher et al. (2014) uses the CMLCA software using the older life cycle impact asessement (LCIA) method from Guinee (2003), and not ReCiPe (Goedkoop et al. 2009). The results in the human toxicity category are similar by applying the high-tech scenario in Sprecher et al. (2014) (41,7 kg 1,4-DCB-eq), but are about three times higher in the baseline scenario. The characterization factors for HF-emissions and other toxicity related stressors may be different for the two methods used. Sprecher et al. (2014) point out in their article "..the characterization factors associated with hydrogen fluoride are quite uncertain". There has been developments in the toxicity-related categories from the framework used by Sprecher et al. (2014) to the Recipe framework used in the current study.

4.4.3 Data quality for the neodymium metal assessment

The results for the carbon footprint from Koltun & Tharumarajah (2014) are higher than in my analysis. 1 kg neodymium (Pr) metal has GHG emissions of 74-75 kg CO_2 eq., being 64 kg CO_2 eq. in this study. There are however large differences in the inventories, with different system boundaries used. Detailed inventory data and results for their study is not available, and could potentially be very different. They do include the monazite mineral in their inventory, in addition to the bastnäsite studied in the current analysis. This increase the energy consumption during processing, as they state monazite to be more energy demanding in their article. Impact assessment framework used is the older Eco-indicator 99 from 2000, which might be the reason for the different results. Emphasis for the study by Koltun & Tharumarajah (2014) was also different, with a goal to compare the impact of the different REEs based on different allocation approaches.

The results from Althaus et al. (2007) are not presented in their article. Their inventory is not as comprehensive as the current. The study use different functional units than the current, and have a different system boundary. Processes in the Ecoinvent database represent the data from Althaus et al. (2007), and approximate results of the impact of 1 kg neodymium and praseodymium oxides were found by performing an allocation with my partitioning values. By comparing with my results from the production of the neodymium (Pr) oxides after the solvent extraction stage, we can confirm that there are large developments in the current inventory. However, there are issues with allocation and difference in the scope for the studies, so these estimated results are not presented here. They do however indicate a doubling of the impact in the climate change category, and there is a difference in one order of magnitude for results human toxicity and marine ecotoxicity. Terrestrial and freshwater ecotoxicity results were similar.

Similar for both Sprecher et al.'s and the current assessment is the importance of the HF-emissions. From the REE inventory, we also know that some single processes are affecting large parts of the impact. This is true for the ammonia-emissions for marine eutrophication and cobalt-emissions for ecotoxicity, both in the separation stage, and the HF-emissions in the in the extraction stage for human toxicity. The results are sensitive upon the assumption of these processes. How the industry control these emissions is important. The values for the scrubbing of HF-emissions, and ammonia and cobalt present in the wastewater are uncertain, as they rest on assumptions or single references only (or both). Although the amounts of wastewater in the separation stage by solvent extraction are great, the emissions of ammonia does seem to be questionably high. For marine eutrophication, the emissions are sensitive for the performance in of the whole windmill system.

Even though the volume of literature about REEs is increasing, the data quality seems to remain unchanged. Many recently published articles reuse the process descriptions of Gupta & Krishnamurthy (2005) and the report of Schüler et al. (2011). The lack of data or poor data quality is the main limitation for LCA practitioners upon construction of a neodymium metal inventory. My LCA is affected by the limitations in the raw data.

It is also important to keep in mind that only one production route, for the Bayan Obo bastnäsite, was investigated in this study. This scope leaves out the monazite from the same ore, and production of rare earths from other sites. The production of REE is site-specific, with different practices used.

Most other energy processes in the inventory are reasonable. I am most confident in the inventoried extraction stage due to the detailed work by Talens Peiró & Villalba Méndez (2013). The material input for beneficiation and solvent extraction is uncertain. To my understanding, the values Althaus et al. (2007) have estimated for the beneficiation process are over 20 years old. There are some other uncertainties as well, as the energy used in the solvent extraction process seems to be very dependent on extraction stages, and no detailed sources where found on this matter. There is also a concern about how the actual RE reduction compare to the aluminium reduction concerning the energy requirements and the direct process emissions. This stage has the largest share of all the foreground processes, and thus largely affects the results from the neodymium metal assessment.

Allocation issues seem to be adequately resolved, but REE prices are fluctuating. Changes in the partitioning values affect all upstream processes, including the extraction, beneficiation and mining stages.

The secrecy of the processing practices within the industry is another obstacle for increasing the data availability, as noted by Talens Peiró & Villalba Méndez (2013) as well. As a result, the major part of research data is only available for the Bayan Obo and the Mountain Pass mine. This existing literature in English literature is based on a small number of older sources.

Schüler et al. (2011) report of an industry in development, but it is unclear how this is reflected in the literature. This remains a problem for researchers wanting to undertake an environmental assessment. The already mentioned literature review article by Navarro & Zhao (2014) explicitly explains the limitations of the LCA of REEs, and supports many of the drawn conclusions in this section.

5 Conclusion

The environmental impact of electric power generation by wind turbines using the DD-PMG design has been investigated in this thesis. It was discovered that the DD-PMG design in general caused less stress on the environment than the conventional design. The increased electricity production and increased compactness in the nacelle, by eliminating the gearbox, in a direct-drive design lead to the improvements. For the process LCA analysis, these were in the range of 6-8 % in impact categories like climate change, particulate matter, photochemical oxidant formation, ozone depletion and terrestrial acidification compared to the analysed conventional design. The reductions related to the higher compactness were from less metal processing and the related decrease in energy consumption.

A decrease of the required copper mass in the DD-PM generator amplified these reductions of the environmental impact. This was particularly the case in categories sensitive for emissions related to metal processing, like freshwater, marine and terrestrial ecotoxicity, human toxicity and freshwater eutrophication. The impact reductions were 13-24 % in these categories.

A large part of the study has been dedicated to the study of environmental impacts of rare earth elements in the NdFeB permanent magnets. The NdFeB magnet merely is a small part of the total system, and relatively speaking has a high environmental impact. It is around 2-4% for 8 of the 13 considered categories, being around 3% for climate change, 4% for human toxicity and 6% for marine ecotoxicity. The impact is dominant for the marine eutrophication category with 41% of the total impact. Because of this, the marine eutrophication category is the only category where the impact increases (by 58 %). Even though there are some reliability issues of the magnitude of this impact, it shows that large point emissions during rare earth processing can greatly affect the environmental performance.

Even though the literature tells about toxicity-related concerns to the rare earth metal production, at the current quality of data available, the analysis shows moderate impact in these categories. Albeit for the impact in human toxicity for the neodymium metal, there is a high normalised impact. It also seems like the methods used in this assessment, with a detailed inventory using the Ecoinvent databased and assessed by the ReCiPe framework, are a development compared with previous LCAs of rare earths.

However, the high impacts caused by the copper in the system detract the attention from the NdFeB-related impacts in all the toxicity categories, in addition to the freshwater eutrophication category. Based on the reputation of REEs, one would think that the NdFeB-related impact for these categories were to be similar or higher than for copper. This is because both copper and REEs are found in a low grade and require advanced processing. It is uncertain how the neodymium metal inventory account for the environmental stress in these categories. At the current point, with the current data, we cannot say that the production of NdFeB is more worrying than the copper production in these categories.

Still, it seems as the inventory does account for the high energy and material input required in this production. The NdFeB does have a higher importance than copper in the more energy-related impact categories like climate change. From the neodymium metal assessment, we know that the electrolysis during the reduction of neodymium oxides to neodymium metal is very energy demanding. The extraction of rare earth metals is material intensive, with high consumption of chemicals, and thus is the processing stage with the highest contributions in many of the impact categories (figure 4-1).

The scenario analysis in section 4.3.5 shows that a potentially increased availability for DD-PMG turbines will better the environmental performance. More certainty about this topic will be feasible as the technology matures. Analysis of reliability statistics of the new, commercial, large turbines installed over the last few years, and an objective assessment of the reliability potential of both technologies should be performed.

A prerequisite for further work on LCAs of rare earth metals is a better data quality, based on empirical practice. Much of the current data are approximations or using proxy data from other similar techniques. This leads to high uncertainties for the neodymium metal assessment.

There are also data challenges related to the DD-PMG technology, but as the innovation currently is high within the field, the data availability should rise in the future. Current literature within the field is associated with cutting-edge research, and characteristic data of commercial designs is scarce and limited – as the commercial designs are few.

For larger, offshore turbines, increasing the reliability of the turbine is important to reduce the cost of energy. The DD-PMG technology seems like a promising solution to achieve this in this segment, reducing the environmental impact at the same time. Even without the increase in reliability, the current thesis, with the current knowledge, supports the development of this turbine technology from an environmental point of view. This life cycle assessment shows that the benefits related to the DD-PMG designs are larger than the potential disadvantages.

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A.1 Ion adsorption clays

Ion-adsorption clays have a different extraction process than the other mineral deposits. The processing is the easiest and cheapest. There are two main methods. The traditional method is performed by moving the overburden material with trucks by mountain top mining. The clay is then removed and the transported. It is prepared for a leaching process into a tank for leaching. Since the REEs are present on the clay in a trivalent cationic state, they are easily extracted from the ore. They are leached out by sodium chloride or ammonium sulphate (Yang et al. 2013).

The mountain top mining leaves gigantic scars in the landscape by excavating the soil. About 0,3 m^2 of surface is transformed per kg REO produced. It permanently eradicates ecosystems. It has been a main driver for biodiversity loss in Southern China. The leaching also produces great amount of wastewater (1 tonne per kg REO) with high concentrations of ammonium sulphate or sodium chloride and heavy minerals that requires treatment. The tailings from the mining has been disposed into streams or valleys nearby the mining site (Yang et al. 2013).

Due to the environmental concerns, the Chinese government in 2011 banned the traditional technique in favor of the in-situ leaching technique. Instead of mining the ore, there are drilled leaching holes. This leaves the surface intact, and at first sight does not interfere with the local vegetation and forests in the same way. Leaching holes are typically 0,8 m in diameter, with a depth of 1,5-3 meters, and a distance of approximately 2-3 m between each other. Yang et al. (2013) report that the process parameters are highly site-specific. A thorough geological survey need to be completed to plan how the leaching process will be performed. Normally a 3-5% ammonium sulphate is pumped down into the main ore. The solution circulates, obtains contact and chemically reacts with the ore to RE sulphates. The leached solution is afterwards pumped up through a second leaching hole. The leaching takes 150-400 days.

One third of the vegetation is still cleared and the process creates over 200 litres of tailings as slurry per kg REO produced. The ground water will be contaminated by ammonium sulphate, with reports of 3500-4000 mg/L water and a 17,8% increase in pH of nearby REE activities. Capillary forces attract the leaching solution towards the surface and contaminate surface water as well, with a 11,4% increase in pH reported (Yang et al. 2013). This also affects and destroys surface vegetation. The surrounding ecosystems are heavily affected by the in-situ leaching. The transformation of the subsoil layer can also cause landslides. This endangers not only the surrounding ecosystems, but also has led to loss of human lives.

After leaching, the RE concentrates are obtained by precipitating the RE sulphates with oxalic acid or ammonium bicarbonate. The concentrates are further separated and refined in the same way as the other minerals.