Development of Circular Economy Core Indicators for Natural Resources

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ROYAL INSTITUTE
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Analysis of existing sustainability indicators as a baseline for developing circular economy indicators

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Abstract

More resources are being defined as critical, which can be attributed to the linear economy of ‘take, make and dispose’. An alternative is to implement the circular economy (CE) which could reduce several negative effects, among other things resource depletion. The aim of this thesis is to identify what current sustainability indicators are lacking to assess a resource with the CE concept. This is done by developing CE core indicators, which then are compared with sustainability indicators. The life cycle of rare earth elements (REE) is used as a case study to validate the CE core indicators. To achieve this literature studies and comparative analysis will be performed.

Existing definitions and indicators of CE were studied to compile a complete set of core indicators. These compiled CE core indicators were then compared with adapted United Nation (UN) sustainability indicators. The UN indicators were chosen after analysing several different sustainability indicator system and their compatibility with the resource perspective. The main differences between the UN indicators and CE core indicators is that the UN indicators does not include economic aspects such as market diversity and social aspects such as consumption behaviour. However, the UN indicator system includes transportation and governance that could be beneficial to include into the CE concept.

The economic viability to perform the CE analysis and non-existing CE indicators for companies and countries were identified as two barriers that could hinder development and efficient use of a CE indicator system. A way to increase the economic viability is to use already generated data for the CE indicator analysis, though the economical aspect has to be studied further. The non-existing CE indicators for companies and countries are counted as a barrier due to the risk of sub-optimisation of one resource.

Additionally, the CE indicator results could be misinterpreted to blame a few for the problems of the resource instead of using the results to improve all parts of the life cycle. Further research is also needed to investigate how, or even if, social aspects such as culture and society could be indicated within a CE indicator system. In conclusion, the UN indicator system could be a good baseline to develop a CE indicator system for a resource though further research is needed.

Key words: Circular economy, indicators, rare earth elements

Sammanfattning

Naturresurser som definieras som kritiska blir fler, bland annat på grund utav den linjära ekonomin som innebär att resurser utvinns, produkter tillverkas och efter användning kastas dessa bort. Förutom problem som uppkommer med minskad mängd resurs i jordskorpan så medför den linjära ekonomin också problem inom avfallshanteringen. Ett alternativ för att minska problemen är att införa en cirkulär ekonomi vilket har som syfte att skapa ett hållbart samhälle genom att eliminera avfall. Inom den cirkulära ekonomin ska resursers kretslopp slutas. Målet för detta projekt är att identifiera vilka brister det nuvarande hållbarhets indikatorer har för att kunna identifiera cirkulär ekonomi potentialen hos en resurs livscykel. För att uppnå detta kommer litteraturstudier och jämförande analyser att användas. Befintliga definitioner och indikatorer av cirkulär ekonomi från bland annat Europa Kommissionen och Ellen MacArthur Foundation har studerats för att hitta olikheter och likheter. Utifrån dessa har en lista med cirkulär ekonomi indikatorer sammanställts.

Flera indikatorer för hållbar utveckling studerades och analyserades med målet att kunna applicera dessa för en resurs livscykel och slutligen för det cirkulära ekonomi perspektivet. Efter analysen ansågs det att Förenta Nationernas (FNs) hållbarhets indikatorer var mest lämpade för livscykelperspektivet. Dessa anpassades sedan och jämfördes med de framtagna cirkulär ekonomi indikatorerna. De största bristerna med FNs hållbarhets indikatorer är otillräckliga ekonomiska aspekter såsom mångfald av aktörer inom resursens industri samt sociala aspekter såsom konsumtions beteende. Dock så har indikationssystemet för hållbarhet ett antal indikatorer som cirkulära ekonomi indikatorerna inte har, såsom transport, vilket med fördel skulle kunna integreras med det cirkulära ekonomi konceptet.

Främst existerar två barriärer för att utveckla och använda indikatorerna effektivt; den ekonomiska genomförbarheten samt brist på cirkulära ekonomi indikatorer för länder och företag. Ett sätt att förbättra den ekonomiska genomförbarheten är att utveckla indikatorerna för att utnyttja befintlig data, dock behöver detta undersökas ytterligare. Om enbart en resurs optimeras för cirkulär ekonomi kan den totala hållbarheten minska, till exempel kan återvinningen av andra resurser minska som en bieffekt av suboptimering för en resurs. Det innebär att cirkulära ekonomi indikatorer är viktigt att utveckla för företags och nations nivå.

En ytterligare risk vid användandet av cirkulär ekonomi indikatorer är att företag och länder misstolkar resultaten eller utnyttjar dessa fel. Det är inte meningen att ett företag eller land ska få skulden för problemen utan resultaten bör användas för att påvisa vad alla kan göra. Dessutom behövs det vidare forskning på hur, och om, sociala aspekter såsom kultur och samhälle kan indikeras på ett vetenskapligt sätt. Sammanfattningsvis kan FNs hållbarhetsindikatorer användas som grund för att utveckla indikatorer för cirkulär ekonomi för en resurs livscykel.

Nyckelord: Cirkulär ekonomi, indikatorer, sällsynta jordartsmetaller

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Abbreviations

3R – Reduction, Reuse and Recycle

CE – Circular Economy

CFL – Compact Florescent Lamps

COD – Chemical Oxygen Demand

EOL – End of Life

EU – European Union

GDP – Gross Domestic Product

GNI – Gross National Income

HDD – Hard disk drives

HREE – Heavy Rare Earth Elements

LCA – Life Cycle Assessment

LCD – Liquid Crystal Display

LED – Light Emitting Diode

LFL – Linear Florescent Lamps

LREE – Light Rare Earth Elements

MFA – Material Flow Analysis

MRI – Magnetic Resonance Imaging

NGO – Non-Governmental Organisation

OECD – Organisation for Economic Co-operation and Development

REE – Rare Earth Elements

REM – Rare Earth Metals

REO – Rare Earth Oxides

UN – United Nations

UNEP – United Nations Environment Program

WEEE – Waste Electrical and Electronic Equipment

WTO – World Trade Organization

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1. Introduction

More resources are being defined as critical and resource depletion is getting more threatening (European Commission, 2014a). This can be related to the current linear economy of 'take, make and dispose', which means that resources are getting extracted, products are manufactured and then thrown away after the use phase (figure 1) (Vaughn, 2014). The resource depletion is therefore not the only problem but the disposed products also needs to be accommodated which can cause negative effects.

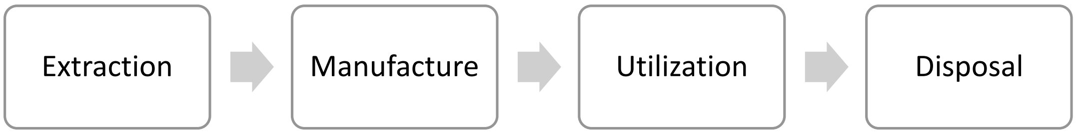

Figure 1. *Linear economy model.*

By changing from a linear economy to a circular economy (CE) many problems could be lessened or even eliminated. Within a CE society no waste for disposal should exists, instead waste should be viewed as a new resource within the economy (figure 2) (Geng and Doberstein, 2008). By following the CE model the pressure on the critical resources can be lessened, the negative effects from disposing waste reduced, and additionally more value could be achieved from the produced resources.

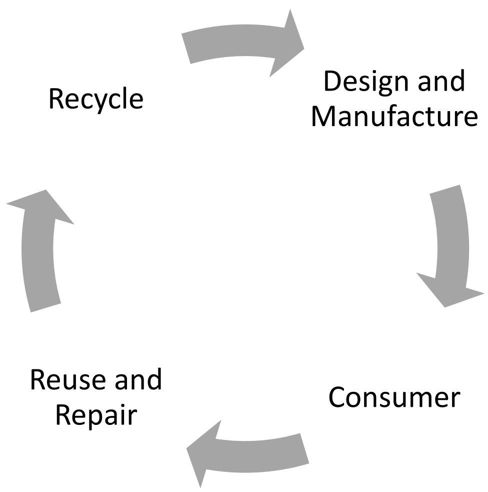

Figure 2. *Circular economy model.*

Currently no attempts exists on how to develop CE indicators for a resource, rather the focus is either at company or regional/national level (Ellen MacArthur Foundation, 2015; Geng, et al., 2012). By addressing the complete life cycle of a resource through the CE concept, the global aspects of the current economy could be assessed. However, CE is a relative new phrase with no clear definition and literature regarding the subject is not coherent. Therefore, this thesis will explore several different definitions and attempts at developing CE indicators to compile a list of CE ‘core indicators’. These core indicators will not be measurable nor have a unit, but will instead include all aspects that needs to be regarded when developing CE indicators for a resource.

The end goal of CE indicators for a resource would be to assess what aspects are most critical and where actions should be implemented to increase the circularity and reduce negative impacts. These results could be used as guidance for governments and companies but also as progress benchmarking by regularly assessing the critical resource. In this report the rare earth elements (REE), which is a group of metals, will be used to validate the CE core indicators that will be developed. The REE are defined as critical and the demand is seemingly only increasing in the near future (Moss, et al., 2013). Within the REE life cycle many phases’ causes harm and the damage could be reduced and value increased by including the REE into the CE concept.

1.1. Aim and Objectives

The aim of this thesis is to develop CE core indicators and identify what existing sustainability indicators are lacking to be able to evaluate a resource with the CE principles. The objectives are as follows:

- Review some of the existing CE definitions and indicators
- Develop CE core indicators from existing definitions and indicators
- Review some of the existing sustainability indicators
- Adapt chosen sustainability indicators for a resource
- Establish differences between CE core indicators and the adapted sustainability indicators
- Use the REE life cycle to validate the developed CE core indicators

1.2. Limitations and Assumptions

To limit the scope of the REE life cycle, it is assumed that consumption and therefore waste management takes place in Europe. Only dysprosium, europium, terbium, yttrium, praseodymium, and neodymium were studied since these are categorized as especially critical. Furthermore, the scope was limited to only study the main intermediate products of the six critical REE mentioned, which are permanent magnets and lamp phosphors.

2. Methodology

For this thesis two main methods have been used, literature review and comparative analysis. This section will describe these methods and how they were used depending on what section of the thesis is regarded. Firstly, literature reviews of REE and CE were conducted followed by a compilation of the CE core indicators. Thereafter an additional literature review on sustainability indicators was performed which resulted in a list of sustainability indicators adapted to a resource. The compiled list of CE core indicators and the list of adapted sustainability indicators was then analysed using comparative analysis. Lastly, the REE life cycle was used to validate the CE core indicators.

2.1. Literature Review

Literature review was used during the entire length of the project to gather the appropriate information. Firstly, information about the REEs and their life cycle was gathered, mainly from academic literature search from KTHB databases and Google Scholar. Since the REEs have been studied quite extensively in recent years, a broad view of the life cycle was provided.

The second part of the literature study was to find definitions of the CE concept and indicators. Similar search engines as before were used to search for academic literature, though other forms of literature were also used, such as publications from administrative authorities, to provide a broad view of the CE concept and its potential indicators.

The last part of the literature study is connected to finding sustainable development indicators that could be adapted for a resource. The goal was to find indicators used on global, national and company level, though this was found to be troublesome since few indicator system exists that includes all aspects of sustainable development.

2.2. Analysis

In this thesis the comparative analysis was mainly used. Firstly, comparative analysis was used to compile the list of the CE core indicators by comparing each CE definition and CE indicators from different stakeholders with each other. By comparing each definition and indicators with one another, the differences and similarities could be identified. This analysis resulted in a list of CE core indicators where no CE aspects was repeated or lost.

Secondly, comparative analysis was used to compare the CE core indicators with the adapted sustainability indicators. In this analysis each category within the different indicator systems were compared with each other to find if some were corresponding. To identify similarities and differences of core indicators within the corresponding categories the same method of comparison were used within each category.

The comparative analysis was also used to validate the CE core indicators by addressing them on the REE life cycle. This was done by comparing each core indicator with the REE life cycle.

3. Life cycle of Rare Earth Elements

The REE consists of 17 elements; the 15 lanthanides, scandium and yttrium (figure 3) (Alonso, et al., 2012). Promethium is one of the lanthanides but is sometimes excluded from REE because it has a short half-life and is not present in the REE deposits anymore (Elshkaki and Graedel, 2014). The REE are divided into heavy REE (HREE), which includes europium through to lutetium and yttrium, and light REE (LREE) which includes lanthanum to samarium (Moss, et al., 2013). All REE have similar properties, though they have individual characteristics, and many are used in green technologies. Green technologies includes wind turbines, low-energy lightning and electric vehicles which many economies rely on for a future sustainable technology development and decarbonisation of the economy (Guyonnet, et al., 2015; Moss, et al., 2013).

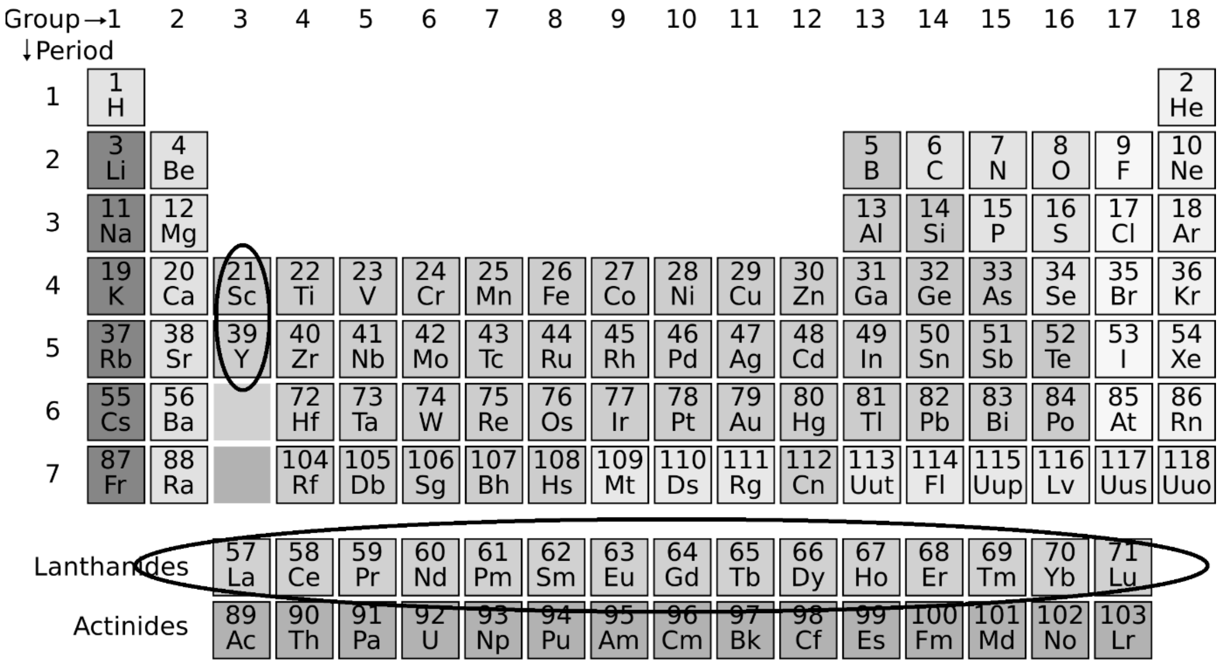

Figure 3. *Periodic table with the REEs circled.*

The name REE is misleading because the minerals containing REE are more abundant than for many other metals, such as copper, but the concentrations are too low in most places for viable extraction (Walters and Lusty, 2011). This together with the extensive processing to separate out individual rare earth metals (REMs) makes REE mining and refining hard to make profitable. In 2011 China stood for 97% of the world production of REE (EPA, 2012), giving them a near monopoly, but in 2014 Chinas share of the REE production had decreased to 75% (SGU, 2014). This reduction of Chinas share on the world market can be attributed to newly open mines in both Australia and USA, though in 2014 China still stood for 90% of the HREE production (SGU, 2014).

In 2010 China started restricting their export of REE which together with an increased domestic investment into REE industries created a supply shortages that drastically increased prices of some critical REEs (Schüler, et al., 2011). The restricted supply and the increasing demand have made REE a critical substance group, but some of the REE are counted as more critical than others often due to the low ratio of that individual REE in the deposits and a high individual demand. A report from the European Commission highlights six REE as especially critical; dysprosium, europium, terbium, yttrium, praseodymium and neodymium (Moss, et al., 2013). The high demand of these six critical REE increase the risk of a surplus of the more abundant REE such as lanthanum and cerium (Binnemans, et al., 2013). Of the six critical REEs, europium, dysprosium, terbium and yttrium are categorised as HREE, while the other two are included into LREE. Instead of examining the whole REE group this study will only focus on these six critical REEs.

3.1. Extraction and Processing

REE does not exist in its metallic form in nature, but as rare earth oxides (REO) in mineral deposits. There are more than 200 known minerals that contains REO but it is generally mined from three: bastnäsite, xenotime and monazite (EPA, 2012). Few extraction sites are exclusively mined for REE, instead they are often a by-product from other mining operations, such as iron ore, titanium and uranium mining (Walters and Lusty, 2011). As figure 4 shows the main source of REMs is from iron oxides at 47% and from ion adsorption clays at 32 % (Peiró, Méndez and Ayres, 2013). Additionally figure 4 shows that generally only ten of the total 17 REE are used, including the six critical (Moss, et al., 2013). All REE deposit have a unique composition of individual REEs, but generally the HREE are scarcer than LREE and generally the most abundant REEs are lanthanum and cerium (Castor and Hedrick, 2006).

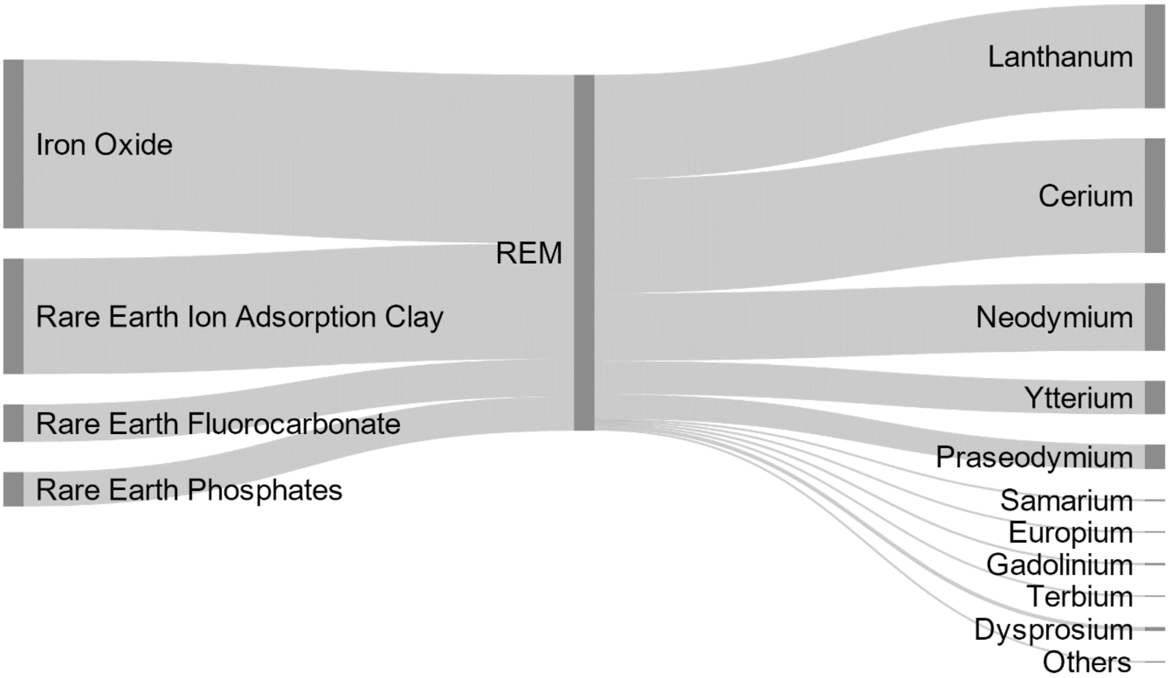

Figure 4. *The sources of REMs and the ratio if the individual REMs adapted from* Peiró, Méndez and Ayres (2013)

The world largest single producer of REE is located in Inner Mongolia, China, and is called Bayan Obo. The main ore is iron oxide and the REE are mined as a by-products of that mining operation (Walters and Lusty, 2011). The mining method used at Bayan Obo is called open pit mining and is used at many other REE mines (Walters and Lusty, 2011). To be able to access the ore, the overburden, which is the soil and rock above, has to be removed. To extract the actual mineral ore blasting and/or drilling is used and then the ore is transported to a stockpile for storage or directly to further processing (Walters and Lusty, 2011). A common method used during the pre-processing of the ore, also called beneficiation, is floatation, and the goal is to increase REO content by concentrating it. (Walters and Lusty, 2011). During the concentration process, large amount of waste is generated, which is called tailings. At the Bayan Obo mine the impoundment for tailings alone covers an area of 11 square kilometres (Schüler, et al., 2011).

The tailings does not only occupies a large land area but it also contains radioactive substances and heavy metals. The stockpiles which contains both ore and sub-ore, which is low grade ore that are not yet suitable for extraction, has an environmental risk due to the leak of toxic substances though runoff, flooding and rainwater (EPA, 2012). These leakages have at the Bayan Obo site polluted the ground water, which has affected the wells, livestock, agriculture and human health in nearby villages (Schüler, et al., 2011). Test of vegetation in the area of Bayan Obo have also shown that the area is contaminated by radioactivity. Additionally an increase in the mortality rate of workers can also be attributed to the radioactivity since they inhale radioactive dust during the crushing process (Schüler, et al., 2011).

To convert the concentrated REO into individual REE different techniques and methods are used, among other things depending on the individual composition of the REO. At the Bayan Obo mine, the concentrate is baked at between 300-600°C with sulfuric acid and then leached with water. This takes the REE into a solution and precipitates out other elements as waste through liquid-solid separation. The REE are then converted into hydroxide by precipitation as double sulphates and then purified using solvent extraction and other methods (Castor and Hedrick, 2006). What all methods, including that used at the Bayan Obo mine, have in common is high consumption of chemicals (Weng, et al., 2013).

Another technique used to mine REE is the in-situ leaching method that is used to extract REE from the ion adsorption clays in Southern China. The ion adsorption clays do not have the radioactive substances usually associated with REE deposits and are generally easier to mine due to the type and location of the deposits (Walters and Lusty, 2011). Additionally, the ion adoption clays have a higher concentration of the HREE than other types of deposits (Cordier, 2015). The in-situ mining method entails drilling 1.5-3 m deep holes that are 0.8 m in diameter at 2-3 m intervals. These holes are then filled with a leaching solution, generally with a concentration of 3-5% ammonium sulphate, which is left to leach for 150 to 400 days. (Yang, et al., 2013). Successfully use the in-situ leaching method require an extensive geological and geotechnical survey to be completed. This makes it possible to customize the chemicals and techniques for each deposit, otherwise only a low REE recovery can be achieved (Yang, et al., 2013).

In 2011, the Chines government put a ban on surface mining and started enforcing the in-situ leaching method of the ion adsorption clay deposits in Southern China. By then the surface mining and heap leaching methods had caused lasting damage, such as permanent loss of ecosystems, soil erosion and human health problems. Supposedly, the in-situ leaching method was introduced to decrease the environmental impacts, but in-situ leaching also has severe environmental impacts. At several mining sites the pH in the surface and ground water has increased between 11-17.8% near the mines. Even after mining the sulphate pollution continues due to the nutrient contamination of downstream waters that increases microbial production of hydrogen sulphide. This sulphide is very toxic for many of the organism and plants in the aquatic environment. (Yang, et al., 2013)

Except water pollution the in-situ leaching method also erodes the soil and causes both mine collapses and landslides. In the Ganzhou region, where in-situ leaching mining is used, over 100 landslides have occurred due to the in-situ mining methods. These landslides not only destroys the ion adsorption clay deposits but is also a risk for human life. Between the years 2004 and 2010, 32 322 fatalities from landslides could be attributed to environmental degradation. Most of these fatalities occurs in the Himalayan mountains and China, and it is predicted that the fatalities of landslides in China are going to increase. (Yang, et al., 2013)

3.2. Manufacturing and Utilization

Since REEs are used in a large variety of products, this section will describe the most common manufacturing and usage of the six critical REE main products. Dysprosium, praseodymium and neodymium, three of the critical REEs, are mostly used in permanent magnets (figure 5). Other uses for the three mentioned REE are in batteries, additives and catalysts. The permanents magnets are mostly used in electrical and electronic devices and electric vehicles, though they are also used in among other things, wind turbines and magnetic resonance Imaging (MRI) equipment (Peiró, Méndez and Ayres, 2013).

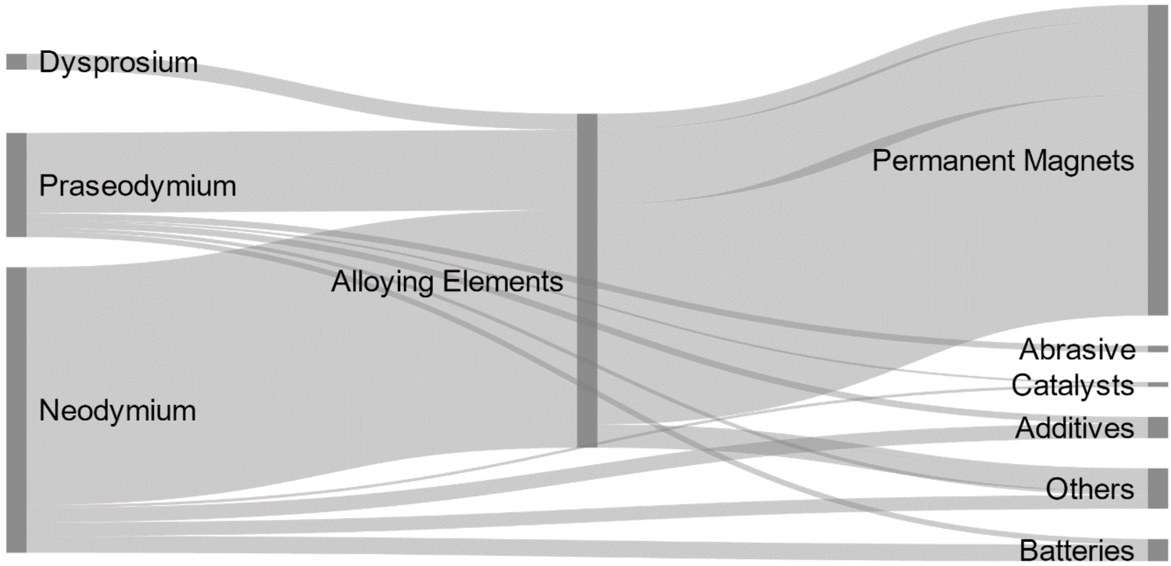

Figure 5. *Substance flow of praseodymium, neodymium and dysprosium. Adapted from* (Peiró, Méndez and Ayres, 2013)

The most commonly used REE containing permanent magnet is the NdFeB magnet (Binnemans, et al., 2013). The magnets consist of a core alloy containing the REE and often have a coating of nickel. Depending on the desired properties of the magnet the core alloy is changed to include different ratios of REE and other metals (Binnemans, et al., 2013). In 2007 China produced 76% of the world's NdFeB permanent magnets and Japan produced most of the rest (Xiaoyue and Graedel, 2011). Around 20% of the magnet alloy is lost in the manufacturing of the magnet (Minowa, 2008).

The use phase of the permanent magnets differs depending on the end-product. In 2013 the biggest category of permanent magnet use was electrical and electronic devices which includes many different products. Some examples of electrical and electronic devices that contains permanent magnets is hard disk drives (HDDs), mobile phones and loudspeakers (Peiró, Méndez and Ayres, 2013). Generally this is a category of products which are not leased or hired but owned by private consumers, which from a circular economy perspective makes it hard to close the loop, though some examples of leasing does exists regarding mobile phones (Vaughn, 2014). Other uses for permanent magnets are in bigger products such as hybrid and electric vehicles, MRI equipment and wind turbines (Peiró, Méndez and Ayres, 2013). These end-products are used during a longer time (Xiaoyue and Graedel, 2011) and presumably have a high collection rate due to the type of ownership.

The other three critical REEs; yttrium, europium and terbium, are mostly used in lamp phosphors (figure 6). Europium is only used in phosphors whereas terbium is used in both phosphors and permanent magnets. As can be seen in figure 6, yttrium is by far the most utilised of the three REEs, and it is used in both lamp phosphors and in the glass and ceramic industries as an additive. The lamp phosphor, which can be green, red and blue, is usually used in lightning devises such as florescent lamps, both linear and compact, but can also be found in liquid crystal displays (LCDs) and plasma panels (Peiró, Méndez and Ayres, 2013). More recently the REE phosphors are being used in light emitting diode (LED) lamps (SGU, 2014; Binnemans, et al., 2013).

Figure 6. *Substance flow of yttrium, europium and terbium. Adapted from* (Peiró, Méndez and Ayres, 2013)

The REE containing lamp phosphors, which also includes metals, are used as the coting inside the lamp and helps with emitting light. Depending on the desired colour of the lamp different compositions and REEs are used. Different types of lamps exists which includes REE phosphors, such as the compact florescent lamp (CFL) and linear florescent lamp (LFL), but all also includes mercury. The mercury content in the lamps classifies them as hazardous waste at end of life (EOL) (Binnemans et al., 2013). The fluorescent lamps have a lifespan of around 6 years (Guyonnet et al., 2015) and they are presumed to have a similar ownerships as small electrical and electronic devices.

3.3. Waste Management

For bigger end-products containing permanent magnets, such as vehicles and wind turbine, only small amounts have reached the waste management system due to their long life expectancy and relative short presence on the market. The small amounts that do exists are not viable to recycle, though in the future a potential high collection rate could provide a good source for recycled REE. Smaller end-products containing permanent magnets in the category of electrical and electronic devices, such as mobile phones and HDDs, does exists in viable amounts in the current waste management system due to its shorter lifespan. The waste stream of HDDs are especially interesting since they are often collected separately due to the potential sensitive information stored on them. Currently only small-scale research recycling is taking place on permanent magnets though a big potential exists within the current waste management. (Moss, et al., 2013)

Most of the REE containing permanent magnets ends up in the waste stream called waste electrical and electronic equipment (WEEE) which has a complex treatment process. This is due to the wide variety of products and complex components this waste fraction entails (El-kretsen, 2015). The fluorescent lamps and LEDs have a similar waste management situation as for WEEE and have a relative high collection rate since it's regarded as hazardous waste (Binnemans, et al., 2013). Currently two of the biggest opportunities of recycling REE in Europe are from permanent magnets in WEEE and fluorescent lamps, since they exists in large enough quantities and are collected within the current waste management system (Binnemans, et al., 2013).

In Europe the formal recycling of WEEE consists of several stages. Firstly the waste fraction is sorted to remove any dangerous products that need special treatment then products are dismantled into different categories such as HDDs and motherboards (Kuusakoski AB, 2014). Though not all WEEE are collected properly and some ends up in incineration ashes and landfills after going through the municipal waste system (Elshkaki and Graedel, 2014; Guyonnet, et al., 2015; Morf, et al., 2013). Lastly, WEEE can also be informally recycled, often after being ship out of Europe as second hand products. This form of recycling takes place without safety equipment and proper facilities and causes both human health problems and environmental damage (Said, 2010). It is assumed that no REE recycling could take place within the informal recycling of WEEE due to the complexity of REE recycling. Even though WEEE are recycled within the formal recycling system currently less than 1% of the total REE are recycled (Graedel, et al., 2011).

Historically the incentive to recycle REE has been limited due to low market prices of virgin REE and lack of efficient recycling technologies. However, in recent year's research has been moving forward on how to recycle REEs and two small scale recycling facilities have been built in France. The primary problem concerning REE recycling from permanent magnets is the dismantling stage because of the variety and complexity of the products. Two different methods on how to recycle REE from permanent magnets in HDDs have been developed, one at the University of Birmingham and one at the company Hitachi in Japan. The Hitachi method entails dismantling in a specially built spinning drum that shakes and vibrates the HDDs until the screws loosens and it falls apart into its original components. At that stage the permanent magnets can be collected manually to either be reused or recycled. (Binnemans, et al., 2013)

The technique developed at the University of Birmingham firstly involves removing the REE containing parts of the HDD to increase the REE ratio. After that, the REE containing parts are exposed to hydrogen at atmospheric pressure. During the hydrogen exposure the nickel coating fall out in flakes and the REE alloy is turned into a powder. Then the HDD parts are rotated in a drum to free the powder and Ni flakes from the rest of the HDD parts. The last stage is to separate out the Ni flakes from the REE powder. The powder can be used directly to manufacture new magnets, though the quality of the new magnets depends on the composition of the recycled magnets. (Binnemans et al., 2013) Recycling of permanent magnets can also take place at the manufacturing stage. As mentioned before the manufacturing process has around 20% loss of REE alloy, though exactly how much depends on the shape and quality of the magnet. Currently some internal recycling at the manufacturing companies exists (Schüler, et al., 2011).

For fluorescent lamps it currently exists two recycling units in Europe, both in France and both managed by the company Solvay. One of the recycling units extracts the phosphor powder from the lamps and the other unit separates out the individual REOs from the powder (Guyonnet, et al., 2015). Depending on what type of lamp different methods to extract the phosphor powder is used, but currently it is only possible for larger CFLs and LFLs. One of the biggest challenges regarding recycling of lamp phosphors is the mercury content which has to be removed (Binnemans, et al., 2013).

I theory it exists three ways of to recycle lamp phosphors, (1) direct reuse into new lamps, (2) separate out individual phosphor for reuse in new lamps or (3) separate out the REE content. As mentioned, it is the larger CFLs and LFLs that generally can be recycled. With the linear tubes the ends can be cut of and the lamp phosphors is blown out. For other shapes, such as the spiral form of the CFLs the lamp is often crushed to access the phosphor powder. However, the crunching process leaves glass-powder that dilutes the phosphor powder and makes the further processing more difficult. In most countries though, no recycling of the lamp phosphor is done and it ends up at landfills after the mercury is either stabilised or removed. (Binnemans, et al., 2013)

Another benefit of recycling, than reducing the need for virgin resource extraction, is the lack of radioactive substances in the recycled REE since it already have been removed. Because of the wide variety of impacts caused by the REE extraction process recycling would have a positive effect on both the environment and human health. Unfortunately the United Nations Environment Program (UNEP) estimates that less than 1% of REE are recycled post-consumer (Graedel, et al., 2011). Though with current projections for future demand, virgin material extraction will still be needed even if 100% recycling could be achieved (Guyonnet, et al., 2015).

3.4. Other Aspects

The life cycle of REEs also have other difficulties which are not connected to any specific life cycle stage. Since the majority of the extraction and production is located in China, much of the knowledge and expertise regarding REE is also located there. The research is not always shared and China has strict rules and legislations regarding foreign companies being involved with the REE industry (Schüler, et al., 2011). China also have invested a lot in REE research, especially at the Batou Institute of Rare Earths (Walters and Lusty, 2011). This results in a knowledge imbalance between China and the rest of the world.

Though the imbalance seems to have somewhat decreased since the prices greatly increased in 2011 (Humphries, 2013) and non-Chinese governments, organisation and companies started researching and investing more into REEs (Buchert, et al., 2009). The interest of REE also have increased due to its vital part of decarbonising the economy and its uses in defence technologies (European Commission, 2014a). A clear problem with the knowledge imbalance is that much of the REE usage and subsequent waste management is not located in China. When regarding the REE waste management in Europe it is likely that the knowledge generated in China would greatly benefit the recycling research if shared.

An additional problem not related to any specific part of the life cycle is the drastically increased prices of some REEs to upwards of 500% during 2011 which can be explained by the export quota imposed by the Chinese government (Haque, et al., 2014). According to the Chinese government the export restriction was imposed to reduce the environmental pressure caused by the extraction process (WTO, 2015). Even though in 2012 the prices had started dwindling down to normal market prices, the Word Trade Organization (WTO) ruled that the restrictions violated the trade rules (WTO, 2015). An additional problem regarding governance is the problems with illegal mining and trading of REE and it is estimated that 30% of the Chinese exports could be illegal (Guyonnet, et al., 2015).

4. Circular Economy

The CE is a concept that aims at building a sustainable society through changing the current linear 'take, make and dispose' economy to a closed loop society where no waste exists (European Commission, 2014b). The linear economy has been built on the idea that resources are infinitive though this is not the case, and more resources are being labelled as critical due to supply issues (European Commission, 2014a). The linear economy has also resulted in environmental damage especially in countries that have had a rapidly increasing economic development, such as China (Geng and Doberstein, 2008). The CE concept could provide a solution of how to continue the economic development without negative impacts on the environmental or human health.

A CE assessment of a critical resources life cycle could provide a better overview of which stages should be focused on to reduce criticality and negative impacts. In this section, different definitions and existing CE indicators will be studied and used for compiling a list of CE core indicators. Furthermore, it is important to remember that each of the following definitions and views of the CE concept have been developed under different circumstances and with different goals.

4.1. Circular Economy Definitions

Even if the vision of a zero waste society is common for all definitions of CE the principles varies somewhat, therefore the CE definitions from Ellen MacArthur Foundation, Circle Economy cooperation, European Commission and Chinese government will be studied further. The European Commission's definition of CE was chosen to be studied due to the geographical boundaries for the REE case study where the consumption and waste management is located in Europe. For a similar reason the definition of CE from China was chosen to be studied since much of the extraction of REE takes place in China (Du and Graedel, 2011b). Both Ellen MacArthur Foundation and Circle Economy are similar organisations that promotes CE through partnerships and projects. Ellen MacArthur Foundation has more partnerships than Circle Economy and also includes several global companies (Circle Economy, 2015b; Ellen MacArthur Foundation, 2015b), though the CE definition from Circle Economy were chosen to complement the Ellen MacArthur Foundation definition in order to provide a broader view of the CE concept.

Ellen MacArthur Foundation

The Ellen MacArthur Foundation has divided the CE definition into principles and characteristics. The principles were developed to be action guides for companies and organisations, whereas the characteristics describes the theoretical CE concept. The three principles for actions are as follows (Ellen MacArthur Foundation, 2015c):

1) Preserve and enhance natural capital
2) Optimize resource yields
3) Foster system effectiveness

The first principle of preserving and enhancing natural capital should be achieved through balancing renewable resource flows and regulate the finite stocks. The second principle is linked to cycling materials, both in pure form and in products, at the highest possible quality. A system that designs for remanufacturing and recycling will also has tight material loops that can save both energy and embedded labour. The last principle involves promoting system effectiveness by designing out negative aspects, such as damage to human utilities that includes but are not limited to food, shelter and health. This principles also includes managing externalities, including land use, air, water, toxic pollution and climate change (Ellen MacArthur Foundation, 2015c). To complement the principles the theoretical CE concept has been described with the following characteristic (Ellen MacArthur Foundation, 2015a):

1) Design out waste
2) Build resilience through diversity
3) Work towards energy from renewable sources
4) Think in systems
5) Think in cascades

By designing out waste it is not only meant that all material loops should be closed, it also includes that biological materials should be non-toxic to facilitate the reintroduction into natural systems and that the man-made materials should be design for efficient material recovery. An efficient material recovery both have a low energy consumption and are able to achieve a high grade of material purity. The idea behind the second characteristic is that a diverse system with modularity, adaptively and versatility is more resilient towards external factors. The third characteristic of working towards renewable energy is straightforward an exhortation to exclude fossil fuels from the energy system. The last two characteristics are focused on how to think when developing a CE for a system. For instance, the system thinking is vital to understand how different parts of the system affects each other and the cascade thinking is an exhortation to create additional value from materials and products. (Ellen MacArthur Foundation, 2015a)

Circle Economy

The Circle Economy cooperative has another approach of defining CE compared to Ellen MacArthur Foundation. Apart from the goal of reducing waste Circle Economy describes the CE concepts as closing material loops and mimicking natural ecosystems when regarding society and businesses. The final goal of CE according to Circle Economy is to manage and recycle materials efficiently and only use renewable energy without having negative impacts on human life or ecosystems. To achieve this final goal Circle Economy has developed six principles that should be followed (Circle Economy, 2015a):

1) Cycle materials infinitely
2) Use renewable energy
3) Support ecosystem services and natural capital
4) Support human health and activities
5) Support society and culture
6) Generate value, both financial and other types

Principles one and two aims at closing material loops and reduce usage of fossil fuels. The other aspects are more ambiguous and Circle Economy does not provide additional explications to the precise meaning behind them. What can be interpreted is that ecosystem services and natural capital are of importance and that social aspects have been divided into two different principles. Human health and activities are categorised into one principle whereas society and culture is divided into another. The last principle regards value generation, though what other kind of value except financial is not explained.

European Commission

The European Commission does not have an official definition of CE that includes principles or characteristics such as the Ellen MacArthur Foundation and Circle Economy, though the CE concept is explained by exemplifying a natural and living ecosystem. Within a living system in the natural world nothing is waste since each component is design to fit its particular place in the cycle and this should be mimicked to achieve the CE concept. The European Commission describes the CE concept by using the following four categories (European Commission, 2014b):

1) Design for CE
2) Sustainable consumer choices
3) Policy in support of the transition
4) Broad participation

The first category of designing for CE explains the importance of designing products and services to fit into the CE concept. For example with design for durability, repair, reuse and recycling. This category also includes changing business models to service-based instead of product-based. The second category elucidates the issues of consumer responsibility and opportunities. This is importance since the consumer choice either keeps the linear economy or forces a change into the CE concept. This category also emphasises that consumer behaviour can be changed through information and surroundings and that the consumer mind set should be changed from 'consumer' to 'user' and from 'owner' to 'sharer'.

The third category describes the importance of policies and frameworks that promotes CE, for example through measures such as the Eco-Design Directive. The broad participation category explains the importance of support from the society to achieve the CE concept, not only from businesses and consumer but also from academia, non-governmental organisations (NGOs) and other stakeholders. (European Commission, 2014b)

Chinese Government

Likewise as the European Commission the Chinese government has not provided a clear definition of what the CE concept actually entails. However, how and why China has created their CE model will show how China views CE. Already in 2002 the Chinese government called their new sustainable development model for CE and aimed at closing the material loop throughout the economic system. China wants to apply the CE concept since the rapid economic growth with the current linear economic system has caused both environmental harm and resource depletion. Among other things, China is facing land segregation, deforestation, acid rains and loss of biodiversity and the CE concept is regarded as a model to continue the economic growth without further harming the environment. (Geng and Doberstein, 2008)

The Chinese CE model has its roots in industrial ecology, also called eco-industrial development, and was from the beginning inspired by both Japan and Germany, which early on developed CE related laws and regulations (Geng and Doberstein, 2008). Similar to the European Commission the Chinese CE model desires to mirror the natural ecosystems within the economy. This does not only mean that waste in one part of the economic system will be a resource for another, but also that competing companies will develop the system, just as species in a natural ecosystem. Furthermore, the model also promotes shared infrastructure and services for companies within the same geographical area, such as eco-industrial parks. (Geng and Doberstein, 2008)

4.2 Review of Existing Indicators

Some attempts at developing indicators for the CE concept already exists and of the four actors studied above only two of them have developed indicators; Ellen MacArthur Foundation and the Chinese government. The indicator system developed by Ellen MacArthur foundation was in collaboration with a company called Granta Design and the indicators are focused on assessing products and companies. On the other hand, the Chinese government indicator system is focused on assessing provisional and national levels though they also includes indicators for industrial parks. This project also found through literature research that these two indicator systems are referred to the most regarding CE indicators.

Ellen MacArthur Foundation and Granta Design

The Ellen MacArthur Foundation in collaboration with Granta Design, which is a material engineering software company, have developed a set of CE indicators. The project that resulted in the indicator system was cofounded by the European Union's financial instrument LIFE. The CE indicators were developed to assess how well a company or a product are adapting towards the circularity concept. The indicators were specifically created to be a decision-making tool for designers but can also be used for internal reporting and rating of companies. The focus for these CE indicators are the technical cycles and materials from non-renewable sources and primarily consists of material circularity indicators but additional complementary indicators can be used. The material circularity indicators consists of four different indicators (table 1) containing material input, utility and waste management, (Ellen MacArthur Foundation and Granta Design, 2015b)

Table 1. *Material circularity indicators for a product*
(Ellen MacArthur Foundation and Granta Design 2015b)

Indicator	Explanation
Input into the production process	How much input is coming from virgin and recycled materials and reused components?
Utility during use phase	How long and intensely is the product used compared to an industry average product of similar type?
Destination after use	How much material goes to landfill (or energy recovery), how much is collected for recycling, which components are collected for reuse?
Efficiency of recycling	How efficient are the recycling processes used to produce recycled input and to recycle material after use?

The indicators shown in table 1 are developed to assess a product but the Ellen MacArthur Foundation and Granta Design also developed a framework of how to perform a company assessment. To assess a company's material circularity a reference product approach is used. This means that for each group of similar products that a company produces, a reference product is chosen. The material circularity indicators shown in table 1 are then used to assess each reference product. Lastly, the results of the reference products indicators are weighted together to create the company's result. The material circularity indicators results in a value between 0 and 1, where a higher score indicators a higher circularity. (Ellen MacArthur Foundation and Granta Design, 2015b)

In addition to the primary CE indicators (table 1) Ellen MacArthur Foundation and Granta Design developed complementary indicators. These indicators are in divided into risk and impact categories and the goal is to provide information of what the risks are and which materials, components and products should be focused on. The complimentary indicators are optional and are not integrated into the material circularity indicators. No complete set of complementary indicators were developed but several example indicators were provided (table 2). (Ellen MacArthur Foundation and Granta Design, 2015b)

Table 2. *Exampels of complementary indicators*
(Ellen MacArthur Foundation and Granta Design 2015a)

Category	Indicator
Risk indicators	Material price variation
	Material supply change
	Material Scarcity
	Toxicity
Impact indicators	Energy use
	CO_2 Emissions
	Water use

As can be seen from table 2, the focus in the first category of risk indicators are materials. The examples given to assess material risk are price variation, supply change, scarcity and toxicity. For price variation an indicator tool was developed during the project but for the other existing indicators and/or index systems were suggested to be used. For example, when regarding the impact indicators for energy usage and CO_2 emissions, it was suggested to use a consequential life cycle assessment (LCA) to verify that the actions do not increase either of them. (Ellen MacArthur Foundation and Granta Design, 2015a)

These indicators were only developed to assess the material circularity of the technical cycles and materials from non-renewable sources, which means that the scope is narrow. Additionally no clear indicators for either social, environmental or economic aspects are included. The complementary indicators are only suggestions of aspects that could be further investigated, and are not integrated into the main indicators. When comparing the indicator system with their own definition, not even the first principle of enhancing natural capital is included.

Within the narrow scope of the indicator system, the material consumption is well indicated and the company and product approach can be beneficial. If a company can analyse their own products and business in an easy and relative cheap way they can make better decision of how to move towards material circularity. Since companies and industries are a vital part of implementing CE on a national level it is important to have company based indicators.

However, the narrow scope with focus only on material consumption can also misguide companies into believing that CE only includes material circularity. The broadness of the CE concept and the overall sustainability thoughts regarding the social, environmental and economical could then be lost. Even though Ellen MacArthur foundation and Granta Design calls them material circularity indicators and not for CE indicators they do connect them to the CE concept. Therefore, they have to be clear that these indicators only include a very small part of the complete CE model.

Chinese Government

The Chinese government sustainable development model implements the CE concept at three levels; micro, meso and macro. The micro-level is the individual companies and includes measures such as eco-design and cleaner production. The meso-level consists of industrial parks where companies collaborates in an industrial symbiosis. Lastly, the macro-level is the provisional and national level that aims at creating a recycling society by addressing production and consumption.

The Chinese CE indicators were developed and adapted from existing indicator systems, such as material flow analysis (MFA) and eco-efficiency indicators. Additionally the so called 3R principle of reduction, reuse and recycle was implemented and the goal of the indicator system is to provide measurable and objective data for decision makers (Geng, et al., 2012). China has developed two sets of indicator systems, one for the macro-level and one for the meso-level (table 3 and 4). The indicator system for both levels have four similar categories; (1) resource output, (2) resource consumption, (3) resource utilization rate and (4) waste disposal and pollutant emissions. The macro-level CE indicators, shown in table 3, consist of 22 indicators divided into the four mentioned categories. As can be seen the category of integrated resource utilization rate has the most indicators, though five of those are the recycling rate of specific materials. The category of resource consumption also has many indicators and all are focused on water and energy consumption.

Table 3. *Chinas natinal level CE indicators* (Geng, et al., 2012).

Category	Indicators
Resource output rate	Output of main mineral resource
	Output of energy
Resource consumption rate	Energy consumption per unit gross domestic product (GDP)
	Energy consumption per added industrial value
	Energy consumption of per unit product in key industrial sectors
	Water withdrawal per unit of GDP
	Water withdrawal per added industrial value
	Water consumption of per unit product in key industrial sectors
	Coefficient of irrigation water utilization
Integrated resource utilization rate	Recycling rate of industrial solid waste
	Industrial water reuse ratio
	Recycling rate of reclaimed municipal wastewater
	Safe treatment rate of domestic solid wastes
	Recycling rate of iron scrap
	Recycling rate of non-ferrous metal
	Recycling rate of waste paper
	Recycling rate of plastic
	Recycling rate of rubber
Waste disposal and pollutant emission	Total amount of industrial solid waste for final disposal
	Total amount of industrial wastewater discharge
	Total amount of SO_2emission
	Total amount of chemical oxygen demand (COD) discharge

As mentioned before the meso-level indicators, shown in table 4, has similar categories as the macro level indicators. The meso-level has 12 CE indicators which are few compared to the macro-level CE indicators. However, the meso-level has more indicators in the category of resource output rate, while the other categories have fewer indicators, compared to the macro-level. The meso-level indicators are more focused on the flow of different resources, such as energy, water and mineral.

Table 4. *Chinas industrial park level CE indicators* (Geng, et al., 2012)

Category	Indicators
Resource output rate	Output of main mineral resource
	Output of energy
	Output of land
	Output of water resource
Resource consumption rate	Energy consumption per unit industrial production value
	Energy consumption of per unit key product
	Water consumption per unit industrial production value
	Water consumption of per unit key product
Resource comprehensive utilization rate	Recycling rate of industrial solid waste
	Industrial water reuse ratio
Waste disposal and pollutant emission	Total amount of industrial solid waste for final disposal
	Total amount of industrial wastewater discharge

A review of the Chinese government CE indicators on both meso- and macro-level by Geng, et al. (2012) showed five specific deficiencies; lack of social indicators, urban/industrial symbiosis indicators, micro-level indicators, absolute material and energy reduction and finally a lack of prevention oriented indicators. Since an important part of the CE concept is to include both economic, environmental and social aspects, it is a major deficiency that no indicators of any social aspects were included. Additionally the Chinese CE concept has been implemented on all levels, including the micro-level, which includes businesses and facilities, but no indicators for this level has been included.

Another indicator that Geng, et al. (2012) identified as missing is an absolute material and energy reduction which is especially interesting for a growing nation such as China since the relative reduction can in fact be an absolute increase. The last point made by Geng, et al. (2012) is that even though the indicators should be based on the 3R model, no prevention measures have been included. In the current Chinese government CE indicator system it is better to recycle that to implement waste prevention since this can lead to less materials for recycling.

Finally some implementation issues have been identified by both Geng, et al. (2012) and Su, et al. (2013) which both highlights the issues of no clear guidelines or standardized process to compile, calculate and present the data and information. This means that each individual organisation and/or local government will interpret the indicators in their own way, which results in non-comparable indicators. Additionally both Geng, et al. (2012) and Su, et al. (2013) identifies the lack of benchmarks and goals as a barrier. They argue that local governments will have a hard time implementing the CE concept since they do not have a clear goal or benchmarks.

Additionally both the macro- and meso-level of indicators are specific, for example the amounts of industrial solid waste for final disposal and emissions of SO_2 are regarded. Despite this level of detail, no indicators for CO_2 emission or other air emissions, except SO_2, are included.

4.3. Compiled Circular Economy core indicators

By comparing each definition and indicator system with one other, differences and similarities have been identified. The similarities have been merged into one category each and then the differences have been added to compile a list of CE core indicators (table 5). Since the definitions and existing indicators addresses different parts of a life cycle and the actors have different perspectives these compiled core indicators gives a broad perspective of the CE concept. The definitions were also included into the compilation of the core indicator since they have a broader scope than the existing indicators.

The core indicators have been divided into five categories; (1) resource productivity, (2) environmental aspects, (3) economic opportunities, (4) social aspects and (5) waste management. Each category has between two and three core indicators. The category resource productivity is focused on the resource and energy consumption but also the ratio of renewable energy (table 5). The core indicator of resource consumption does not only include the amounts of resource used but also how efficient the usage is. Similarly, the energy consumption core indicator include both total amounts and the efficiency. Regarding the efficiency several aspects such as waste generation during manufacturing and design choices needs to be considered.

Table 5. *CE core indicators with explinations.*

Category	**Core indicator**	**Explanation**
Resource Efficiency	Natural resource consumption	The total amount and efficiency of natural resource use
	Energy consumption	The total amounts and efficiency of energy use
	Renewable energy	The ratio of renewable energy use
Environmental aspects	Natural capital	How the resource and its industry affects the environment and ecosystems in all life cycle stages
	Water consumption	The total amount of and efficiency of water use
Economic Opportunities	Generate value, both financial and other	The profitability of the resource industry
	Market diversity	The number of companies and countries involved in each life cycle stage
Social Aspects	Human health	How the resource and its industry affect human health in all life cycle stages
	Society and culture	How the resource and its industry affect society and culture in all life cycle stages
	Consumption behaviour	How consumers behave regarding the products containing the resource
Waste Management	Recycling	Both the ratio and efficiency of recycling
	Waste for final disposal	The total amount of waste for final disposal

The second category (table 5) views the impacts on the environment which includes water consumption and ecosystem services such as climate regulation and water purification (BISE, 2015). Water consumption could be counted as a resource in the previous category, but since water is a vital and natural resources, it should have its own core indicator. Another important aspect of CE is the economic value of the actions. The CE model should not be a charity project but rather be a viable economic model that can compete with the current linear economy. Therefore, one of the core indicators in the economical category is to generate value where the financial value can be complemented with other values such as knowledge. Additionally a indicator for diversity of the market was included since a key point of CE is that a diverse system is more resilient towards external impacts (Vaughn, 2014).

Furthermore, CE core indicators should include social aspects such as human health and impact on society (table 5). Social aspects have mostly been inspired by the cooperation Circle Economy's definition of CE, and then been complemented with an additional core indicator for consumption behaviour. Regulations and company actions can guide or force this consumption behaviour in certain directions. The final category of waste management only includes two core indicators; (1) recycling and (2) waste for final disposal (table 5). These are developed to show both how far the CE concept has been implemented but also to address the efficiency of the waste management. In a fulfilled CE society, the last indicator of waste for final disposal should show that no materials are disposed of. Though it is important to remember that recycling of resources is only the last resort and that more efficient usage during the product life cycle has a bigger gain within the CE concept.

5. Sustainability Indicators

In this section of the report, several sustainability indicators are going to be reviewed to assess their compatibility with the resource perspective. From this review one of the sustainability indicator system is going to be adapted to the resources perspective. Later on the adapted sustainability indicators will be compared with the CE core indicators from section 4, table 5, to assess what the suitability indicators are lacking to be compliant with the CE concept.

5.1. Review of Sustainability Indicators

Several sustainability indicator systems have been developed and in this section the indicators from the European Commission, United Nations (UN) and Organisation for Economic Co-operation and Development (OECD) are going to be reviewed. The European Commission sustainability development indicators were chosen to be studied since this thesis has an assumed consumption and waste management located in the Europe regarding the REE. The UN indicators are developed for the national level just as the European Commission indicators but have a different scope and perspective. The OECD indicators were chosen to be reviewed since they provide an economical point of view that the other indicators are lacking.

European Commission

The European Commission sustainability indicators consists of over 130 indicators in total, though some have been identified as headline indicators within 10 different categories (table 6). These indicators were developed to monitor the European Union (EU) sustainable development strategy (European Commission, 2015c). Most of the indicators (table 6) are self-explanatory but as can be seen the category of good governance does not include a headline indicator. Good governance includes three operational indicators; (1) policy coherency and effectiveness, (2) openness and participation and (3) economic instruments and the goal is to create consistency between the actions on the local, reginal, national and global levels (European Commission, 2015a). Additionally the indicator “common bird index” in the category of natural resources includes operational indicators for biodiversity, freshwater resources, marine ecosystems and land use. The overall aim of these natural resource indicators are to circumvent overexploitation, improve management and identify the value of ecosystem services (European Commission, 2015b).

Table 6. *European Commissions sustainability indicators* (European Commission, 2015c)

Category	Headline Indicator
Socio-economic development	Real GDP per capita
Sustainable consumption and production	Resource productivity
Social inclusion	Person at-risk-of-poverty or social exclusion
Demographic changes	Employment rate of older workers
Public health	Healthy life years Life expectancy at birth
Climate change and energy	Greenhouse gas emissions Primary energy consumption
Sustainable transport	Energy consumption of transport relative to GDP
Natural resources	Common bird index
Global partnership	Official development assistance as share of gross national income (GNI)
Good governance	*No headline indicator*

As can be seen in table 6, these 10 different categories includes the economic, social and environmental aspects, which are important within sustainable development. Though when addressing a resource life cycle these indicators does not provide either the global level or the smaller factory level. The European Commission sustainability indicators are focused on national level and for the life cycle perspective indicators such as life expectancy at birth are not relevant. Energy is included in relation to climate change with focus on greenhouse gas emissions even though many other environmental problems exists. These other environmental problems, such as eutrophication and acidification, are addressed in the category of natural resources through the impacts they have on the ecosystems and biodiversity rather than indicating the individual problems.

United Nations

The UN sustainability indicators consists of 14 main categories, which then are divided into subcategories (table 7). Each category has between two and six subcategories that have their own headline indicators. In total there are 50 headline indicators, which is a part of a larger set of indicators that includes 96 indicators. The full table of the 50 headline indicators from the UN can be viewed in appendix 1. The UN indicators should be applied at the national level and does not have a one goal but can rather be used for both decision-making, measure progress and as a tool for communicating ideas and values. Furthermore, the UN indicator system was developed to be executed with data most countries already compiles. (United Nations, 2007)

Table 7. *United Nations sustainability indicators* (United Nations, 2007)

Category	Subcategory
Poverty	Income poverty
	Income inequality
	Sanitation
	Drinking water
	Access to energy
	Living conditions
Governance	Corruption
	Crime
Health	Mortality
	Health care delivery
	Nutritional status
	Health status and risks
Education	Education level
	Literacy
Demographics	Population
	Tourism
Natural hazards	Vulnerability to natural hazards
	Disaster preparedness and response
Atmosphere	Climate change
	Ozone layer depletion
	Air quality
Land	Land use and status
	Desertification
	Agriculture
	Forests
Oceans, seas and coasts	Coastal zone
	Fisheries
	Marine environment
Freshwater	Water quantity
	Water quality
Biodiversity	Ecosystems
	Species
Economic development	Macroeconomic performance
	Sustainable public finance
	Employment
	Information and communication technologies
	Research and development
	Tourism
Global economic partnership	Trade
	External financing
Consumption and production patterns	Material consumption
	Energy use
	Waste generation and management
	Transportation

By comparing the European Commission's indicators in table 6 with the UN indicator categories in table 7, it can be seen that the UN indicator system is more detailed and contains more categories than the European Commissions. This can be attributed to the fact that the UN indicators should be applicable to all countries in the world whereas the European Commission's indicators only have to regard the EU countries, which are more uniformed. The European Commission indicator system has also been developed to assess a specific strategy that further limits the scope. Furthermore, it can be seen from table 7 that the UN indicator system also includes the economic, social and environmental aspects of sustainable development just as the European Commission indicator system.

Some economic aspects are included in the UN indicators, though not in an applicable way for either CE or a resource perspective. Furthermore, the geographical boundaries of a country also limits the indicators when regarding the life cycle of a resource. Just as the European Commission indicators, neither the global nor the facility level are included, though the UN indicators have some of the aspects when regarding the life cycle of a resource, such as material and energy consumption. The UN indicator system is mostly focus on the social and environmental aspects of sustainable development with many indicators for how the environment is affected by human activities. However, some of the social indicators, such as poverty and demographics, are not applicable when regarding a resource perspective.

Organisation for Economic Co-operation and Development (OECD)

The OECD indicators are developed to help countries to assess and compare their green growth process. The idea behind OECDs green growth concept is good economic development with preserving and enhancing the natural resources. The OECD green growth indicators consists of 25-30 different indicators though table 8 shows the headline indicators within each topic with short explanations. The OECD green growth indicators are divided into four different categories; (1) environmental and resource productivity, (2) natural asset base, (3) environmental quality of life and (4) economic opportunities and policy response (table 8). (OECD, 2015)

Table 8. *OECD indicators for green growth* (OECD, 2015)

Topic	Headline Indicator	Explanation
Environmental and resource productivity	Carbon productivity	GDP growth related to production- and demand-based CO_2 emissions
	Energy productivity	How much energy is necessary to generate one unit of GDP? What is the share of renewable energy?
	Material productivity	How much materials are consumed to produce one unit of GDP?
Natural assets base	Freshwater	How do countries use water relative to their population or resources?
	Land	What shares of the total land area are dedicated to agriculture, pastures and meadows, forests?
	Wildlife	How many animals and plant species are threatened?
Environmental quality of life	Access to sewage treatment	What share of the population is connected to the sewerage with primary, secondary, tertiary treatment?
Economic opportunities and policy response	Research and Development	What share of the GDP goes to research and development? And what share is directed at energy or the environment?
	Patents	How many patents are applied for in each environmental sector?
	Development assistance	What share of official development assistance is in favour of green growth?
	Taxes	What share of total tax revenue is raised though environmentally related taxed? How much applied to energy or road transport?

By comparing the OECD indicators with the UN and European Commission indicators, it can be seen that the focus of the OECD indicators are more economical and not as broad. Even though the OECD green growth indicators are economically focused they do provide indicators for the environment and at least have acknowledge the social and health aspects of sustainable development. They are also developed to assess a country's sustainability, which is a limitation when regarding a resource perspective. Though the OECD indicator system is somewhat more focused on the input, outputs and the economic angle, which is positive for the CE concept. When comparing the OECD indicators with the UN indicators it can be seen that the UN system has more indicators for the environmental aspects but also has a broader indicator base for the social aspect.

5.2. Selected Sustainability Indicators

The different sustainability indicators reviewed have advantages and disadvantages though both the European Commissions and UN indicators have a broader sustainability perspective than the OECD indicators. The economic aspects are important for the CE concept, though they already have been studied thoroughly and can be reproduce, therefore the OECD indicators will not be used for comparison with the CE core indicators. Between the UN and European Commission indicators the UN includes more indicators from additional categories and therefore will be used for comparison with the CE core indicators in table 5, section 4, since a broader scope is more compliant with the CE concept. However, the UN indicator system does not have the resource perspective and includes some additional categories that are of no interest for the CE concept and will therefore not be considered.

Adapted United Nations Indicators

The UN sustainability indicators were adapted to be more applicable for the life cycle of a resource perspective (table 9). Firstly, four main categories were removed; poverty, education, natural hazards and demographics since they are purely for the national level of sustainability and are not needed when assessing a resource. Additionally in the health category, the subcategories of nutritional status and health care delivery were removed for the same reason. In the main category of economic development, the three indicators of (1) public finances, (2) information and communication technologies and (3) tourism were also removed. Furthermore, in the economic development category the subcategory of macroeconomic performance was changed to economic performance. In addition the subcategories with hence be called core indicators to correspond with the developed CE core indicators.

Table 9. *Adapted UN core indicators for the resource perspective*

Category	Core indicators
Governance	Corruption
	Crime
Health	Mortality
	Health status and risks
Atmosphere	Climate change
	Ozone layer depletion
	Air quality
Land	Land use and status
	Desertification
	Agriculture
	Forests
Oceans, seas and coasts	Coastal zone
	Fisheries
	Marine environment
Freshwater	Water quantity
	Water quality
Biodiversity	Ecosystems
	Species
Economic development	Economic performance
	Employment
	Research and development
Global economic partnership	Trade
	External financing
Consumption and production patterns	Material consumption
	Energy use
	Waste generation and management
	Transportation

6. Analysis of core indicators

In this section the adapted UN core indicators, seen in table 9, will be analysed to see how applicable they are for the CE concept by comparing them with the CE core indicators in table 5, section 4. Firstly, the different categories were compared to correlate the similar categories for further comparison (table 10). Table 10 shows that the UN indicators have more categories though most are concentrated in the compiled CE category of environmental aspects. This does not mean that the UN indicator system has additional aspects, only that is has a different level of detail. In addition, each system has a category the other does not; CE core indicators have waste management and the UN core indicators have governance (table 10). Each correlating category will be studied separately to further analyse the differences.

Table 10. *Comparison between CE categories and adapted UN categories*

CE categories	UN categories
Resource productivity	Consumption and production patterns
Environmental aspects	Atmosphere
	Land
	Oceans, seas and coasts
	Freshwater
	Biodiversity
Economic opportunities	Economic development
	Global economic partnerships
Social aspects	Health
Waste management	
	Governance

6.1. Resource productivity

The first category to be assessed is the CE category of resource productivity (table 11). The category has three CE core indicators; (1) resource consumption, (2) energy consumption and (3) renewable energy. The correlating UN category is consumption and production patterns which has four different core indicators; (1) material consumption, (2) energy use, (3) waste generation and management and (4) transportation. As can be seen in table 11 the CE core indicator of resource consumption correlates to the UN core indicator of material consumption and they can be viewed as equal.

Additionally the CE core indicators of energy consumption and renewable energy can be viewed as equal of the UN core indicator of energy use, since this UN core indicator can include both consumption and ratio of renewable energy (table 11). Furthermore, the UN core indicator system has two additional core indicators; (1) waste generation and management and (2) transportation. Since waste generation and management is important within the CE concept, this is a separate category. The CE concept do not have a category or core indicator for transportation and even though it can be viewed as both resource and energy consumption, it could be interesting to add a transportation into the CE concept. In summery the two indicator systems are similar within this category.

Table 11. *Resouce productivity category*

CE core indicators	**UN core indicators**
Natural resource consumption	Material consumption
Energy consumption	Energy use
Renewable energy	
	Waste generation and management
	Transportation

6.2. Environmental aspects

The second CE category to be compared is environmental aspects, which correlated to five different UN categories; (1) atmosphere, (2) land, (3) oceans, seas and coasts, (4) freshwater and (5) biodiversity. For the indicators this means that the CE core indicators only have two core indicators whereas the UN includes 14 different core indicators (table 12). As mentioned, this merely suggests a different level of detail within the indicator systems and does not mean that the CE core indicators have a narrower scope. The CE core indicator of water consumption can be compared with two the UN core indicators of water quality and quantity. All the other UN core indicators can be included into the CE core indicator of natural capital, which shows the different level of detail (table 12).

Table 12. *Enviornmental aspect category*

CE core indicators	UN core indicators
Water consumption	Water quality
	Water quantity
Natural capital	Climate change
	Ozone layer depletion
	Air quality
	Land use and status
	Desertification
	Agriculture
	Forests
	Coastal zone
	Fisheries
	Marine environment
	Ecosystems
	Species

6.3. Economic Opportunities

The CE category of economic opportunities correlates to the two UN categories of economic development and global economic partnerships. This translates to two core indicator within the CE core indicator system whereas the UN indicators system includes five different core indicators (table 13). Generate value and economic performance are the only two core indicators that are similar within this category (table 13). The CE indicators have one additional core indicator; market diversity. As mentioned earlier the core indicator for market diversity is meant to show how diverse and therefore the resilience of the life cycle of the chosen resource.

The UN indicator system has another approach regarding the economic aspects and includes employment, research and development, trade and external financing (table 13). These core indicators may not be directly connected with the CE concept but plays an important part for the economic opportunities and stability from a sustainability perspective.

Table 13. *Economic Oppertunities category*

CE core indicators	**UN core indicators**
Generate value, both financial and other	Economic performance
Market diversity	
	Employment
	Research and development
	Trade
	External financing

6.4. Social Aspects

The CE category of social aspects correlates to the UN category of health (table 10). As can be seen in table 14 the CE category has three different core indicators; (1) human health and activities, (2) society and culture and (3) consumption behaviour. The UN category of health has two core indicators; (1) mortality and (2) health status and risks, which both correlates to the CE core indicators for human health and activities (table 14).

The other two CE core indicators does not have corresponding UN indicators (table 14). The core indicator for society and culture is quite vague and has to be investigate further. The CE core indicator of consumption behaviour is very important for the CE concept but does not have a correlating UN core indicator since this concept is not relevant for the sustainability of a country. In summery both indicator system includes the health perspective though other social indicators such as cultural indicators are harder to develop and does not exist for the UN core indicators and only as a concept and not a clear definition for the CE indicators.

Table 14. *Social aspects category*

CE core indicators	**UN core indicators**
Human health	Mortality
	Health status and risks
Society and culture	
Consumption behaviour	

6.5. Additional Aspects

As mentioned earlier each indicator system has a category that the other does not. The CE core indicator system has waste management whereas the UN indicator system includes governance. The UN indicators includes the waste generation and management but within the material consumption category. For the CE concept, waste management is of a high importance and therefore has its own category. The CE waste management category includes two different core indicators; (1) recycling and (2) waste for final disposal. Both these two CE core indicators can be included into the UN category of material consumption and the core indicator of waste management.

On the other hand, the UN category of governance does not have a corresponding category or core indicator within the CE indicators. The UN governance category includes two core indicators; (1) corruption and (2) crime. These may serve a bigger purpose when assessing a countries sustainability but these may also be important for the resource perspective.

6.6. Summary of Differences

In summery the main deficiencies of the UN indicator system are the lack of economic core indicator for market diversity and social core indicators of consumption behaviour and cultural aspects. They are also lacking the design and material efficiency thinking within the category of resource productivity. However, the CE concept could be further expanded with inspiration from the sustainability indicators system with aspects such as governance, employment and transportation. The categories that differs the most between the CE and UN indicators are social aspects and economic opportunities whereas resource productivity and environmental aspects are somewhat the same.

7. Validation of core indicators

In this section the CE core indicators are going to be applied on the REE life cycle to validate that all aspects of CE are included. This validation will show if the broad scope of CE has been applied into the indicators and if any impacts of the REE life cycle is not included. Additionally, it could show a rough estimate of how well the REE life cycle is compliant with the CE concept. The validation is going to be divided into the core indicator categories; resource productivity, environmental aspects, economic opportunities, social aspects and waste management.

7.1. Resource productivity

The category of resource productivity has three different core indicators; resource consumption, energy consumption and renewable energy. For the core indicator of resource consumption, both total amounts and the efficiency of the resource use is of interest. To assess the total amounts of REE consumption the in-use stock has to be evaluated, which Du and Graedel (2011a) have already made a first estimate of. It can also be assumed that the REE resource efficiency can be improved since the criticality of REE is relative new and the industry still has to streamline the production processes. As mentioned earlier the design choices are important when assessing the resource efficiency. For the REE these choices also have to be investigated further. For example, the shape of permanent magnet could affect the manufacturing loss of REE alloy and the permanent magnets could be substituted to non-REE containing magnets. Additionally some of the waste management issues could be solved by better designing for disassembly and recycling.

No clear view of the energy consumption during the REE life cycle was given, though it can be assumed that the extraction, processing and production are energy intensive and since the majority takes place in China a large proportion of the energy mix is coal (EIA, 2015). The energy consumption during the use phase and waste management also has to be regarded. For the six critical REE described in section 3, most end-products require energy during the use phase. When regarding energy consumption of REEs the permanent magnets use in wind turbines should also be mentioned since they are used in renewable energy production.

7.2. Environmental Aspects

The two core indicators in the category of environmental aspects are natural capital and water consumption. The core indicator for natural capital is a large category and can include many aspects such as land, forests, agriculture and biodiversity. For the REE life cycle the large areas polluted during the extraction phase is a major problem causing harm to several environmental aspects. First of all deforestation and the sub-sequential loss of habitat is inevitable when establishing and expanding the mine, both at the mine location, stock pile areas and the roads and other infrastructure needed for the mine.

Additionally the pollution from the mines causes' long term harm which means that during a long time after the mine has closed the area will still be affected. The factories that manufacture the REE products can also cause serious harm to the environment through pollution. Furthermore, the waste management also has to be regarded for example, the informal recycling can cause both harm to both humans and the environment. When regarding the water consumption within the REE life cycle not much is known neither within extraction, manufacturing or waste management. However, the emissions from the mines pollutes the groundwater in the area, which affects nature, human health, agriculture and livestock.

7.3. Economic Opportunities

Generation of value and market diversity are the two core indicators in the category of economic opportunities. When it comes to generation of value the REE market has been quite unstable with shortage of supply and corresponding prices increases (Schüler, et al., 2011). This is a serious economic risk for the companies with relies on importing REE resource or REE products. Even though the supply is restricted, the demand is increasing due to the important role of REE in green technologies. Furthermore, REEs can also generate other than financial value, for example through the green technologies they are used in. Since the green technologies can reduce energy use and increase the ratio of renewable energy they can be defined as other than financial value.

The second core indicator in the economic opportunity category is the market diversity. China had a near monopoly of the REE extraction and production, which has affected the REE life cycle, as mentioned in section 3. The Chinese domination does not only makes the system less resilient, as seen when the Chinese export quota was imposed, it also makes it harder for other countries and companies to compete. This is because China can keep the prices relative low due to among other things the existing knowledge and infrastructure. However, as explained in section 3, the Chinese domination on the REE market has lessened and become more diverse. Still China stands for a large part of the extraction and production, especially for the HREE, and has much of the knowledge connected to the REE life cycle.

7.4. Social Aspects

The social aspects category has three different core indicators; (1) Human health and activities, (2) society and culture and (3) consumption behaviour. From the REE life cycle several links between environmental damage and human harm can be seen, among other things the groundwater pollution affects agricultural land and livestock. From there the pollutants enter the human food chain and causes harm. Additionally, the working conditions in the mines affects the workers' health, among other things through radioactive dusts that have increased the mortality rate (Schüler, et al., 2011). Also the in-situ mining locations have an increased risk of landslides which both affects workers and the close by villages (Yang, et al., 2013). Furthermore during informal recycling human health can also be harm due to no safety equipment and pollution of close by areas (Said, 2010).

When it comes to the effects on society and culture it becomes harder to assess since no study to date has included this aspect. For future studies it will be interesting if, and how, the society and culture have been changing near the REE extraction sites. What can be said from the use phase is that no clear changes of products use have been done, since primarily REE are not used in completely new products but rather update old ones, as seen in section 3.

The last core indicator of consumption behaviour varieties greatly due to the many different products that REE are used in. For example the usage of small electrical and electronic devices such as mobile phones has a bigger risk of being thrown away in the municipal waste instead of being collected as WEEE (Naturvårdsverket, 2009). The consumer behaviour concerning hybrid or electric vehicles differ, since they are more expensive the likelihood of reuse through a second hand sale increases. Though from section 3 it can be seen that currently REE products are being collected properly but not recycled. Therefore, it can be concluded that currently it is the waste management that has to change rather than the recycling behaviour.

7.5. Waste Management

The last category of waste management that has two core indicators; (1) recycling and (2) waste for final disposal. The most apparent deficiency concerning waste management is the lack of REE recycling (Graedel et al., 2011). Since the waste management system have not adapted to the increase of REE containing waste no large scale recycling is done, even though several recycling techniques are being researched. As mentioned earlier the recycling can be made more efficient if the REE containing waste can be separately collected to increase the REE ratio of the waste. Most of the REE are currently thus included in the core indicator of waste for final disposal. Another waste problem connected to the REE life cycle is the vast amounts of mining waste generated during the extraction phase.

7.6. Analysis of CE core indicators for REE

When addressing the life cycle of the six critical REEs from a CE perspective several things can be determined without having to do a full CE indicator analysis. The large negative impacts from the extraction process and the lack of recycling are two aspects that needs to be addressed to include the REE into a CE. As mentioned earlier even with complete recycling, extraction will be needed (Guyonnet, et al., 2015), which makes it especially important to address the issues connected to the extraction phase. Additionally a vital part of a CE is to recycle what cannot be repaired or reused, which does not occur with REE products. Increased recycling leads to increased raw material, which will reduce the need for virgin material and therefore reduce the damage from the extraction process.

However, several other aspects of the REE life cycle is not known or needs to be further assessed with a measurable CE indicator system. In CE theory, smarter design would lead to better material circularity and efficiency, though how much is not known for the REE life cycle. Therefore, the importance of design choices needs to be investigated. Additionally, the manufacturing process needs to be investigated further to assess the CE core indicators of this aspect. Since the six critical REEs investigated in this thesis are mostly used in permanent magnets and lamp phosphors the manufacturing of those would be especially interesting to investigate.

The lack of communication between actors within the life cycle becomes apparent when studying the REE life cycle. The waste management industry and manufacturers needs to collaborate to increase the recycling efficiency. With input from extraction companies, the recycling could be even more improved. Assessing the REE through a CE indicator system could provide a communication platform between the different actors and stakeholders. For example, it could provide a good incentive if companies saw the impacts a pure waste fraction have on the recycling efficiency, which could lead to raw material within their own company. Furthermore, this could potentially lead to more closely collaborations between companies within the life cycle.

The UN core indicators for transportation and crime could be of interest when regarding REE. As established in section 3, the REE life cycle takes place on a global level with extraction mostly in China and then distributed, to among other places Europe. With this global life cycle, it can be assumed much transportation is needed, and this aspects would be interesting to investigate further. The UN core indicator of crime, under the category of governance, could also entail important information regarding the REE since some mines are operated illegal and additionally REE are illegally exported from China (Guyonnet, et al., 2015).

The analysis of the CE core indicators compared to the REE life cycle shows that the main problems of the life cycle is addressed and that several areas with lacking information is identified. This validation shows that the CE core indicators can be used to assess a critical resource to identify where the main impacts occur in the life cycle.

8. Discussion

Part of the aim of this thesis was to identify what the existing sustainability indicators are lacking to be able to use them for assessing the CE potential of a resource, such as the REE. As summarised in the section 6, the UN core indicators lack market diversity and social indicators compared to the CE core indicators. Even though the category of resource productivity is somewhat the same between the compiled CE core indicators and adapted UN core indicator, the CE core indicator system includes more aspects such as design and material efficiency. In this section the barriers, problems, difficulties during the project, generalisation and further research will be discussed.

In summery the study of CE definitions and existing indicators resulted in CE core indicators that included all aspects of the CE concept. Thereafter, existing sustainability indicators were reviewed, which resulted in the adaptation of the UN core indicators. The UN core indicators and the CE core indicators were then compared and analysed to find the differences and similarities. Since many of the core indicators were similar, the UN sustainability indicators could be used as a baseline for further development of CE indicators. The REEs were then used to validate if the CE core indicators were applicable on a critical resource. The validation reviled that the impacts of the REEs were included into the CE core indicators and that areas, such as the manufacturing of intermediate and end-products, needs to be studied further for a complete CE analysis.

8.1. Barriers

To be able to both develop and efficiently use CE indicators barriers needs to be overcome. Firstly, it is important to assess if an analysis with CE indicators would be economically viable to perform in relation to the potential benefits. An important aspect from the UN indicator system that should be mimicked is that preferable data already generated should be used for the assessment. Even though this may not always be possible for the CE indicator case, it should be the goal.

Furthermore, the lack of academically acknowledged CE indicators is a barrier. It is important that viable CE indicators for both countries and companies are developed to help promote CE. Though it would be beneficial if the country, company and life cycle perspective indicators were developed together since much will be similar.

8.2. Problems

Several different potential problems exists with the development and implementation of a CE indictor system that needs to be discussed and addressed. A possible risk is that a company or country are depicted as bad and gets all the blame for the problems within the resources life cycle. When regarding the REE life cycle it is highly plausible that China would become the scapegoat and get most of the blame for the problems. However, this is not the intent of the CE indicators and communication is needed with the whole life cycle to implement the CE concept.

Another problem connected to companies and countries could be misinterpretation of the CE indicator results. For instance when regarding the REE life cycle, it may be easy for manufacturing companies to disregard their own role in the life cycle since the most apparent problems are lack of recycling and the harmful extraction. Furthermore, designers may feel that changing their design will not do much when regarding the larger scale. In this case, regulations and other incentives such as consumer demands are needed to promote the CE concept.

Furthermore, when regarding only one resource sub-optimisation is a risk. This sub-optimisation may occur in all different stages of the life cycle and can affect the CE of other resources, countries and the whole world. For example, an increase of one recycled material may reduce the recycling efficiency of another, which can cause an overall reduction of the regions compliance with the CE concept. Therefore, system thinking is important and needs to be regarded when assessing the CE potential of a resource.

One of the main deficiencies of the UN indicators identified in the analysis is the lack of social indicators for society and culture. However, it may not be possible to objectively assess or measure these kinds of social aspects. It could be possible to identify changes in a society or culture, though to conclusively link those to a resource or business could be impossible. In addition, it would be hard to objectively define the changes as good or bad from the CE perspective. Still the idea of promoting and supporting societies and cultures should be regarded within the CE concept and sustainable development even though these aspects may not be suitable to indicate or measure.

For the CE indicator system, it is important not to lose the complete scope of the CE concept. For example, the Chinese CE indicators reviewed in this report have a strong focus on recycling which mean that within that indicator system recycling is more valued than waste prevention. If the focus instead is on the material circularity, such as the Ellen MacArthur foundation and Granta Designs CE indicators, the social and environmental aspects are lost. For the ultimate CE goal of a sustainable society all of the aspects are important to include, otherwise the CE concept is reduced to a recycling and reuse procedure.

Furthermore, the data collection and generation for calculating the potential CE indicators have to be regarded. Since resources life cycles often extend over the whole globe, data from many different countries will be needed for the assessment. The data from different countries may not be generated or compiled in the same manner, which makes it hard to unify and use for the CE indicators. As mentioned, it should also be a goal to use already compiled data as far as possible.

8.3. Difficulties during the project

The main difficulty during this thesis was the different definitions and explanations of the phrase and concept CE. Though the phrase CE is used quite often no clear definitions exist, which results in many different meanings behind the concept. This made the literature study about CE complex and ultimately limitations were needed to narrow down the CE concept. This resulted in focusing the literature study on presumably relevant CE definitions for this thesis.

8.4. Generalisation

This thesis highlights the problems with the unclear definitions of CE and the lack of suitable indicators even though both companies and governments often use the phrase. However, potential CE indicators for a resource could provide a good insight into critical resources such as the REE. In the long-term perspective the improvements of specific resources could be shown if the analysis was performed regularly. In addition different resources circularity could be compared to assess which is more critical. The ultimate goal of the CE indicator system would be to reduce criticality and negative effects caused during the resources life cycle.

8.5. Further research

Some of the areas that are needed be investigated further have already been mentioned. First, this thesis should provide a baseline for further investigation into the potential development of CE indicators for a resources life cycle. In addition, CE indicators for companies and nations are also needed to be developed further with a broader perspective then the current indicator systems provides. Even though the UN indicator system can be used as a baseline for developing measurable CE indicators, the detailed UN indicators have to be further studied and adapted to the resource perspective.

Finally, research into both environmental and social aspects are needed. For the environmental indicators the level of detail have to be investigated and decided, for example either the emissions or the environmental problem caused by the mission can be indicated. Additionally the possibility and practicality of indicating society and culture from a sustainable development perspective needs to be researched.

9. Conclusion

This thesis has viewed the possibility of using sustainability indicators as a baseline for developing CE indicators. This was done by developing non-measurable and non-unit CE core indicators that included all aspects of CE. In conclusion, the UN sustainability indicators have a potential to be adapted to the CE concept. Though several areas needs to be investigated further, such as the potential to impact on culture and which level of detail is most appropriate to indicate natural capital aspects. Furthermore, this thesis has identified that sub-optimisation for the regarded resource is a risk and therefore CE indicators are needed for both companies and nations. An additional risk when developing CE indicators is that only a few aspects of CE are included. In such a scenario, the full potential of implementing CE is reduced to a material flow analysis or a recycling procedure.

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Appendices

Appendix 1 [UN Headline Indicators]

The table below shows the UN headline indicators for sustainability (United Nations, 2007).

Subcategory	Headline Indicator
Income poverty	Proportion of population living below national poverty line
Income inequality	Ratio of share in the national income of highest to lowest quintile
Sanitation	Proportion of population using an improved sanitation facility
Drinking water	Proportion of population using an improved water source
Access to energy	Share of household without electricity or modern energy services
Living conditions	Proportion of urban population living in slums
Corruption	Percentage of population having paid bribes
Crime	Number of international homicides per 100,000 population
Mortality	Under-five mortality rate
	Life expectancy at birth
Health care delivery	Percentage of population with access to primary health care facilities
	Immunization against infectious childhood diseases
Nutritional status	Nutritional status of children
Health status and risks	Morbidity of major diseases such as HIV/AIDS, malaria, tuberculosis
Education level	Gross intake ratio to last grade of primary education
	Net enrolment rate in primary education
	Adult secondary (tertiary) schooling attainment level
Literacy	Adult literacy rate
Population	Population growth rate
	Dependency ratio
Tourism	
Vulnerability to natural hazards	Percentage of population living in hazard prone areas
Disaster preparedness and response	
Climate change	Carbon dioxide emissions
Ozone layer depletion	Consumption of ozone depleting substances
Air quality	Ambient concentration of air pollutants in urban areas
Land use and status	
Desertification	
Agriculture	Arable and permanent crop land

Forests	
Coastal zone	Percentage of total population living in coastal areas
Fisheries	Proportion of fish stocks within safe biological limits
Marine environment	Proportion of marine area protected
Water quantity	Proportion of total water resource used
	Water use intensity by economic activity
Water quality	Presence of faecal coliform in freshwater
Ecosystems	Proportion of terrestrial area protected, total and by ecological region
Species	Change in threat status of species
Macroeconomic performance	GDP per capita
	Investment share in GDP
Sustainable public finance	Debt to gross national income (GNI) ratio
Employment	Employment population ratio
	Labour productivity and unit labour costs
	Share of woman in wage employment in the non-agricultural sector
Information and communication technologies	Internet users per 100 population
Research and development	
Tourism	Tourism contribution to GDP
Trade	Current account deficit as percentage of GDP
External financing	Not Official Development Assistance given or received as a percentage of GNI
Material consumption	Material intensity of the economic
Energy use	Annual energy consumption, total and by main user category
	Intensity of energy use, total and by economic activity
Waste generation and management	Generation of hazardous waste
	Waste treatment and disposal
Transportation	Modal split of passenger transportation

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