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Critical Resources in Clean Energy Technologies and Waste Flows
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PhD Thesis
April 2015

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PhD thesis, April, 2015

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Preface

The research work presented in this thesis was conducted for a PhD degree in Energy and Environmentally Efficient Technologies at the Department of Chemical Engineering, Biotechnology and Environmental Technology of University of Southern Denmark (Faculty of Engineering). The supervision of this PhD work was ensured by Professor Henrik Wenzel. The PhD research work has been carried out as part of the research project TOPWASTE (www.topwaste.dk), partially funded by the Danish Council for Strategic Research.

This PhD thesis consists of a synopsis of the research work presented in two published, and four submitted papers. Throughout the thesis, these papers are referred to by the names of the authors and the Roman numerals I – VI (e.g. Habib et al. (IV)). The thesis is based on the following papers:


In addition, the following publications have been made during this PhD work (not included in the thesis):


Peer-reviewed conference papers:


In addition, the work carried out during this PhD was presented at the following conferences/seminars:


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What made this challenging PhD possible and indeed, what made this work what it is today, is the marvelous supervision provided by my supervisor, Henrik Wenzel. Words are simply not enough to express my indebtedness for your belief in me throughout this PhD, which has undoubtedly provided me the motivation needed in keep going. Thank you for your incredibly important supervision and mentorship throughout this journey, and for your wisdom, sharpness, and your endless support that has made me a completely different researcher today. Thank you for your faith in my ideas and creative research approaches, no matter how peculiar and anomalous they may have seemed at first.

Special thanks go to Prof. Thomas E. Graedel for hosting me as a visiting researcher at the Center for Industrial Ecology, Yale University. The discussions I had with you regarding my research ideas and the methodological approaches have definitely helped me in getting closer to achieve my objectives. I am extremely grateful to my dear colleague and friend, Lorie Hamelin, for your infinite encouragement, intellectual and administrative support and mentorship from time to time. Thank you for your endless support, positivity and enthusiasm.

Thank you all my colleagues and friends at the International Life Cycle Group at SDU, you really made this journey come through. Thank you, Marianne Wesnæs, Ole Dall, Birgitte Lilholt Sørensen and Henrik Grüttner for all your kindness. Special acknowledgement goes to Ciprian Cimpan for always being there whenever I needed. Similarly, thank you, Keshav Parajuly and Peter Klausen Schibye – I really enjoyed and learned a lot while working with you. I would also like to express my deepest gratitude to Andreas Peter Vestbø and Tom Ellegaard for facilitating the experimental work. Special thanks to Erika Machacek, Jessika Luth Richter, and Polina Klossek for ensuring the success of our joint venture. Thank you, Jin Mi Triolo and René Park Triolo for the technical assistance regarding the cover page. Sincere thanks to all those people who were never tired of my unlimited queries!

Crucial to this PhD journey was the endless support and love of my family, especially my parents – Zaib and Habib. The inspiration and motivation provided by you has always helped me in moving forward. Thank you my sweet sisters Hina, Zaini, Aini and Seemal, and my lovely brother, Hasan. I still wonder how you always made me laugh at the peak of my struggles. I am truly nothing without all of you!
Summary

The modern society in which we live today is dependent on metals. Metals are the basis of our infrastructure and the technology, without which it is hard to imagine the modern life. Metals are non-renewable by nature, implying that the Geological Resources of metals are finite. Their unprecedented extraction from the earth especially during the last two centuries has raised concerns regarding their long-term availability to meet the demand of future generations.

A special concern for the availability of metals for the wider deployment of clean energy technologies in future has been voiced more frequently during the recent years. The existing state-of-the-art clean energy technologies such as the wind turbines and electric vehicles use significant amounts of the so-called specialty metals such as rare earth elements for the specific functionalities required. Rare earth elements have been classified as critical resources by both the European Union and the USA, due to their estimated high supply risk and increasing importance in modern high-tech applications. It is, thus, justified to ask if a broad-scale installation of clean energy technologies in future will be constrained by decreasing availability of metals, in particular the rare earth elements.

A literature survey has revealed the historic cases of how metal resource criticality has expressed itself so far. Three times in recent history, mankind has experienced such metal resource ‘crises’ or in a more neutral term: incidents of metal supply disruption. These cases comprise the cobalt supply disruption in the 1970s, the palladium supply disruption in the 1990s and the rare earths supply disruption in 2010-2011. Three key observations are drawn from these cases of supply disruption, i.e. that:

- The cause of the supply disruption was in all cases of a geopolitical nature, i.e. the supply being dominated by a single producing country from which the supply for different reasons was reduced on a short notice. Geological scarcity as such has not been the cause of supply disruption historically.
- The effect of the supply disruption was in all cases market price oscillation, i.e. a steep price increase that in all cases after a period (of 5 years for cobalt and palladium, and 2-3 years for rare earths) dropped back to the price level, it had before the increase.
- The incident in all cases led to the opening of new mines in other countries, technological substitutions of the critical metal by other solutions, and to increased recycling.

An overall aim of this PhD study has been to enhance our understanding of potential resource constraints for the clean energy technologies in future, where the research can be divided into four main research lines:

1) Exploring rare earths supply limitations for the emerging clean energy technologies, and the role of recycling in lowering these supply limitations
2) Contributing to advances in resource criticality assessment by developing a methodological framework to assess resource criticality in a dynamic and technology specific perspective, demonstrated with the case of direct-drive wind turbine technology

3) Mapping the societal stocks and flows of rare earths in order to estimate their recovery potential from the existing and future waste flows

4) Contributing to the advances in recovery of resources including rare earths from waste by tracking their flow in a conventional waste electrical and electronic equipment (WEEE) treatment facility, and highlighting the ability of existing waste treatment for the efficient recovery of rare earths.

The first research line involved developing four scenarios regarding the demand of two key rare earth elements, namely neodymium (Nd) and dysprosium (Dy), for the clean energy technologies such as wind turbines and electric vehicles as well as for other background end-use sectors by 2050. The primary supply was projected until 2050 by following the historical trend based projection, whereas the secondary supply was estimated by assuming different end-of-life (EoL) recycling rates of rare earths for various end-use products. The results have clearly shown that projected supply cannot meet the forecasted demand of the developed scenarios. Either a highly accelerated rate of mining is required to satisfy the estimated high demand of Nd and Dy in the scenarios or a radical change in technologies compared to today’s state-of-the-art is required to avoid the technological dependency on Nd and Dy by substituting them with other solutions. Recycling does not seem to play a significant role in reducing the gap between the estimated high demand and the projected primary supply in the short-to-medium term future. However, recycling is likely to provide a major supply on the longer term and, thus, also play a major role in reducing the degree of monopolistic supply, i.e. reducing the geopolitical supply risk of rare earths in the future. Furthermore, the results have shown that the depletion of Geological Resources of rare earths is not a concern in the foreseeable future – we are not likely to run out of rare earths as such for several hundred years, even in highest demand scenarios.

In the framework of the second research line, a resource criticality assessment methodology applying a dynamic and technology specific perspective has been developed. This methodology has been demonstrated with the help of the current state-of-the-art direct-drive wind turbine technology, using rare earth based permanent magnet i.e. neodymium-iron-boron (NdFeB) magnet in its generator. The results have clarified that the direct-drive wind turbine concept as such is not dependent on rare earth elements. A so-called product design tree approach is applied to investigate options for substituting permanent magnet solutions by alternatives, which reveals that there are alternative solutions available at all levels of design from the very conceptual level of generator technology to the detailed level of magnet technology. Substitutions do involve both performance and resource trade-offs, which in turn are then subjected to further assessments.
In the framework of the third research line, a detailed material flow analysis (MFA) of NdFeB magnets has been carried out for Denmark from 2012 to 2035. This study has presented the detailed chemical composition and weight of NdFeB magnets contained in 20 different end-use products representing seven product categories. The results have revealed that the amount of rare earths contained in the NdFeB magnets found in the existing waste flows is significantly low. This small amount of rare earths is dispersed over thousands of EoL products, making them less attractive for the recycling companies to recover in an economically feasible manner. The major end-use products of NdFeB magnets such as wind turbines and passenger vehicles have long lifetimes that delay their appearance in the waste stream. Notwithstanding the current low recovery potential of rare earths from waste, the amount of rare earths in the future waste flows is estimated to be considerably high, which may render the opportunity for economically feasible recovery of rare earths in the future.

The fourth and last research line involved tracking the flow of rare earth elements along with the other resources present in computer hard disk drives (HDDs) in a conventional WEEE treatment facility located in Denmark. This treatment plant employ the shredding based processing of WEEE, where the EoL products are first shredded into smaller pieces followed by the separation of different metals from each other with the help of magnetic and so-called eddy-current separators. The results have shown a complete loss of rare earths while processing in this WEEE treatment facility. This is mainly because of the brittle nature of NdFeB magnets converting them into powder once shredded. This powder apparently retains its magnetism and thus sticks to the ferrous surfaces within the plant as well as to the output ferrous fractions. The flow of resulting output material fractions of the WEEE facility was traced until the final recovery in metal smelting processes to delineate the final recovery potential of different resources such as aluminium, steel and copper contained in the EoL computer HDDs. The results have shown only 10% (weight/weight) overall material loss during the whole process chain.

The contribution of this PhD work to resource assessment methodological approaches lies within three main aspects of resource criticality assessment:

- **Geological scarcity**: understanding the dynamics
- **Geopolitical supply risk**: understanding the significance and the dynamics
- **Vulnerability to supply disruption/importance of supply risk**

The nature of these contributions is briefly summarized here:

**Geological scarcity**: Most of the traditional resource assessment methods such as many of the ones proposed for and used in life cycle assessment (LCA) have been *static* in their approach towards assessing the geological scarcity or availability of resources. They often compare the use of resources in a given system to
the known available reserve at a given point in time showing, thus, an indicator of the depletion time of this static entity/quantity of reserve. But estimates of geological entities such as reserve and reserve base of metal resources are dynamic in nature, meaning that they develop over time due to the advancement in technology, discovery of geological resources, and changing economic conditions. This PhD work has contributed to the understanding that the dynamics of reserve estimates due to such developments are indeed very significant, and that the assessment of the risk of resource depletion does not make sense based on a static reserve estimate.

**Geopolitical supply risk:** As the three historic cases of metals supply disruption show, the highest risk of supply disruption in practice has been of a geopolitical nature, which in turn can be related to both political, social, governance, economic and environmental issues. In none of the resource assessment approaches applied for LCA so far, the geopolitical aspects are included. This is a point worth considering in the further development of the life cycle impact component of LCA. In the more recently developed approaches to resource criticality assessment, the geopolitical dimension is included as one of the criticality indicators, but always in a static perspective, as the quantification of the two main indicators behind the assessment of geopolitical supply risk, i.e. the Herfindahl-Hirschman index (HHI) and the worldwide governance indicators (WGI), is always done based on data for a specific point in time. This PhD has contributed to including a more dynamic perspective on the geopolitical supply risk by showing how the HHI can be significantly reduced in the future, partly by increased recycling, partly by new mining operations developing towards a geographical distribution representing the distribution of reserves.

**Vulnerability to supply disruption:** It has been found during this work that resource criticality assessment has strong analogies to Risk Assessment of chemicals and chemical production and storage facilities, and that the development of resource criticality assessment methodology can benefit from understanding this analogy. Traditional risk assessment consists of two factors. The first factor is the risk or probability that an incident (accident/chemical release to the environment) can happen. The second factor is the effect on humans or ecosystems that such a release can have, i.e. the vulnerability of the affected system to such a release. Resource criticality assessment consists of two analogous factors. The first is the supply risk, i.e. the risk or probability of a supply disruption happening. The second is the vulnerability of the affected system to such a supply disruption. Understanding this second factor, thus, leads to the acknowledgement that the applied methodological approaches so far, with respect to what has been termed the ‘importance of supply risk’, do not allow for a sufficient understanding of the vulnerability of the affected countries, regions, systems or economies to a potential supply disruption. Many approaches have used the overall economic significance of a given resource, i.e. in how big a part of the economy the resource today is used, as an indicator for the importance of a supply risk to the system/economy. Looking at the three historic incidents of supply disruption, it is evident that the ease of substituting the resource by technological approaches is a decisive
factor for how big a problem a supply disruption becomes. Some methodological approaches do look into options for resource substitution. But these approaches apply an element-to-element level based on the physical and chemical properties of elements, e.g. that copper can be substituted by another element based on conductivity properties. Such an approach to assessing vulnerability has validity, but it also overlooks the larger part of technological substitution options and underestimates the capability of technological development to release technical systems from dependency on specific resources.

This study applies a much broader approach to vulnerability assessment by using a technology specific approach and by looking at options to substitute for a specific resource dependency, not only at the elemental level, but at all levels of product design, from the very overall conceptual design choices to the very detailed component solutions. From the applied direct-drive wind turbine case, it was found that substitutability is very high, and options to release the design of this product from dependency on Nd and Dy exist at all levels of design. By understanding the analogy to risk assessment, it has become evident that such a technology specific assessment must be applied in order to really understand how vulnerable the assessed systems are to a supply disruption. Any other approach may easily underestimate how easy a system can release itself from a resource dependency by technological substitution measures. This approach has, moreover, been judged realistic for further investigation of the key research question of this study, i.e. the question of whether resource criticality can be a constraint for the future development and full scale implementation of clean energy technologies. In the most advanced future renewable energy scenarios applied in this work, it was found that out of the technologies and sectors demanding the rare earths of Nd and Dy, only few constituted the majority of the demand. Within the scope of one or two more PhDs/post docs, it is realistic to do technology specific assessments of those key technologies, and thereby get a good impression of whether they are very vulnerable to supply disruptions of key resources, or whether technological substitutions can be found just as easily as they were here found for the direct-drive wind turbine technology.
Dansk sammenfatning

Vores moderne samfund er afhængigt af metaller, de danner basis for vores infrastruktur og den teknologi, som udgør grundlaget for hverdagen i dag. Metaler er ikke-fornybare af natur, og det indebærer, at de Geologiske Ressourcer af metaller er endelige. Den stadigt stigende udvinding af metaller fra jorden gennem især de sidste to århundreder har givet anledning til bekymring for deres langsigtede tilgængelighed for fremtidige generationers behov.

En særlig overvejelse, der har været ofte udtalt i de senere år, handler om tilgængeligheden af de nødvendige metaller for en større skala anvendelse af grøn energiteknologi i fremtiden. Eksisterende state-of-the-art grøn energiteknologi, såsom vindmøller og el-biler, anvender væsentlige mængder såkaldte special-metaller som fx sjældne jordarter af hensyn til deres specifikke funktionelle egenskaber. Sjældne jordarter er blevet karakteriseret som *kritiske ressourcer* af både EU og USA på grund af deres vurderede høje forsyningsrisiko og stigende betydning i moderne højteknologiske anvendelser. Det vurderes derfor velbegrundet at spørge, om en større skala udbredelse af sådanne energiteknologier i fremtiden vil være begrænset af faldende tilgængelighed af metaller, herunder de sjældne jordarter.

En gennemgang af litteraturen har afdækket de historiske tilfælde af, hvordan ressource kritikalitet for metaller har udtrykt sig indtil nu. Tre gange i nyere historie har menneskeheden oplevet ressource 'kriser' for metaller, eller med en mere neutral formulering: tilfælde af faldende forsyning af metaller. De tre tilfælde omfatter kobolt forsyning i 1970’erne, palladium forsyning i 1990’erne og forsyningen af sjældne jordarter i 2010-2011. Tre hovederkenkelser kan uddrages af disse tre historiske eksempler:

- **Årsagen til den vigende forsyning** var i alle tilfælde af geopolitisk natur, dvs. at forsyningen var domineret af en enkelt producenter nation, hvorfra produktionen af forskellige årsager blev reduceret med kort varsel. Geologisk sparsomhed som sådan har historisk ikke været årsag til vigende forsyning.
- **Effekten af den vigende forsyning** var i alle tilfælde oscillation af markedsprisen, dvs. en brat prisstigning, som i alle tilfælde igen faldt til niveauet før stigningen efter en periode (på 5 år for kobolt og palladium og 2-3 år for de sjældne jordarter).
- **Begivenheden førte** i alle tilfælde til både åbning af nye miner i andre lande, teknologiske substitutioner af det/de kritiske metaller og til øget genvinding.

Et overordnet mål med dette PhD studie har været at øge vores forståelse af mulige ressourcebegrænsninger for fremtidig grøn energiteknologi, og projektets forskning kan inddeles i fire hovedlinjer:
1) At afklare forsyningsrisici for sjældne jordarter for kommende grønne energiteknologier og den rolle genvinding kan have i forhold til at reducere forsyningsrisici

2) At bidrage til forbedring af metodegrundlaget for vurdering af ressource kritikalitet ved at udvikle et metodegrundlag for vurdering af ressource kritikalitet i et dynamisk og teknologispecifikt perspektiv, demonstreret med direct-drive vindmølle teknologi som eksempel

3) At kortlægge samfundets lagre og strømme af sjældne jordarter med det formål at estimere potentialet for at genvinne dem fra eksisterende affaldsstrømme

4) At bidrage til forbedret genvinding af ressourcer, herunder sjældne jordarter, fra affald ved at afdække deres strømme og skæbne gennem et konventionelt anlæg til behandling af elektronikaffald og belyse anlæggets evne til effektivt at genvinne sjældne jordarter

Den første hovedlinje har omfattet udvikling af fire scenarier for fremtidens energisystem og deres efterspørgsel efter to væsentlige sjældne jordarter, nemlig neodymium (Nd) og dysprosium (Dy), til energiteknologier som vindmøller og el-biler såvel som samfundets baggrundstillstand i andre sektorer i 2050. Den primære forsyning (minedrift) blev fremskrevet til 2050 via en trend-baseret projektion, mens den sekundære produktion fra genvinding blev estimeret ved at antage forskellige end-of-life (EoL) genvindings procenter for sjældne jordarter i de forskellige typer slutprodukter. Resultaterne heraf viser klart, at den fremskrevne produktion/forsyning ikke kan dække den fremtidige efterspørgsel. At dække den fremtidige efterspørgsel vil kræve enten en stærkt accelereret mindrift eller en radikal ændring af state-of-the-art teknologi for at undgå den teknologiske afhængighed af sjældne jordarter. Genvinding kan ikke spille nogen betydelig rolle på kort til mellemlangt sigt. Men på langt sigt vil genvinding kunne dække en stor del af produktionen og dermed også spille en væsentlig rolle i at reducere graden af monopol på markedet, dvs. reducere den geopolitiske forsynningsrisiko af sjældne jordarter. Endelige viser resultaterne, at udtømming af de Geologiske Ressourcer som sådan ikke er en bekymring i forudsigelig fremtid – vi løber ikke tør for sjældne jordarter som sådan i flere hundrede år, selv i de scenarier med den højeste efterspørgsel.

Inden for rammerne af forskningens anden hovedlinje er udviklet en metode til vurdering af ressource kritikalitet, som anvender et dynamisk og teknologispecifikt perspektiv. Denne metode er demonstreret gennem et eksempel på state-of-the-art direct-drive vindmølle teknologi, som anvender permanente magneter baseret på sjældne jordarter, dvs. neodymium-jern-bor (NdFeB) magneter i generatoren. Resultaterne herfra har afklaret, at direct-drive vindmølle konceptet som sådan ikke er afhængigt af sjældne jordarter. En såkaldt produkt design-træ tilgang er anvendt til at undersøge muligheder for at substituere permanente magneter, og det har afklaret, at alternative løsninger uden brug af sjældne jordarter findes på alle niveauer fra det overordnede konceptuelle generator design til konkrete teknologier for permanente magneter. Alternativerne involverer trade-offs for både præstation and ressourceforbrug, som efterfølgende er vurderet yderligere.
Den tredje hovedlinje har omfattet en detaljeret materiale flow analyse (MFA) for NdFeB magneter for Danmark fra 2012 til 2035. Dette studie har presenteret den detaljerede kemiske sammensætning og vægt af i alt 20 forskellige slutbruger produkter inden for syv forskellige produktkategorier. Resultaterne viser, at mængden af sjældne jordarter i NdFeB magneter i eksisterende affaldsstrømme er bemærkelsesværdigt lille. Den ringe mængde er endvidere fordelt over tusinder af EoL produkter, hvilket gør dem mindre økonomisk attraktive for genvindingsvirksomheder at genvinde. De større slutbruger produkter indeholdende permanenter magneter, såsom vindmøller og personbiler, har lange levetider, som forsinker deres tilstedevarelse i affaldsstrømmen. På trods af deres aktuelle ringe tilstedevarelse i affaldsstrømmen, vurderes mængden af sjældne jordarter i fremtidige affaldsstrømme derfor at være signifikant, hvorfor genvinding i fremtiden vurderes økonomisk muligt.

Den fjerde og sidste hovedlinje har omfattet at følge strømmene af ressourcer, herunder sjældne jordarter, tilstede i computer harddesk drives (HDDs) gennem et konventionelt anlæg til behandling af elektronikaffald beliggende i Danmark. Dette anlæg anvender shredder teknolgi til behandling af affaldet, hvor indholdet af EoL produkter først neddeles til småstykker i shredderen, hvorefter de forskellige metaller separeres ved hjælp af magnetiske og såkaldte eddy-current separatorer. Resultaterne har vist et fuldstændigt tab af sjældne jordarter gennem et sådant anlæg. Det skyldes hovedsageligt, at NdFeB magneter af natur er skøre og derfor pulveriseres i shredderen. Pulveret bevarer tilsyneladende sin magnetiske egenskab, hvorfor det hæfter til de magnetiske overflader i anlægget og i affaldets andre jernholdige emner. De udgående materialesstrømme fra anlægget blev fulgt nedstrøms indtil deres endelige oparbejdning i metalmelte processer, hvor det endelige indhold af metal ressourcer som aluminium, stål og kobber i EoL computer HDD blev genvundet. Resultatet heraf viser, at kun omkring 10% (vægt/vægt) af ressourceindholdet i HDDs tabes som helhed for hele proceskæden.

Dette PhD projekts bidrag til metodeudvikling ligger inden for tre aspekter af vurdering af ressource kritikalitet:

- Geologisk sparsomhed – forståelse af dynamikken
- Geopolitisk forsyningsrisiko – forståelse af betydningen og af dynamikken
- Følsomhed for vigende forsyning/vigtigheden af forsyningsrisiko

Karakteren af disse bidrag opsummeres kort her:

**Geologisk sparsomhed:** De fleste af de traditionelt anvendte ressource vurderingsmetoder, såsom mange af dem der anvendes i Livscyklusvurdering, LCA, er *statiske* i deres tilgang til vurdering af geologisk sparsomhed eller tilgængelighed af ressourcer. De sammenligner ofte brugen af en ressource i et givent system med den kendte tilgængelige reserve af denne ressource, og giver således en indikator for
forsyningshorisonten af denne reserve ud fra denne statiske kvantitet. Men estimater af geologiske forekomster såsom reserver og såkaldt 'reservebase' af metalressourcer er dynamiske af natur, dvs. de ændrer sig over tid på grund af teknologisk udvikling, nye opdagelser af ressourcer og forandrede økonomiske vilkår. Dette PhD projekt har bidraget til at forstå, at denne dynamik af reserve estimater på grund af sådanne udviklinger er meget betydelige, og at en vurdering af risikoen for udtømning af en reserve af en given ressource ikke giver mening ud fra et statisk estimat på et givent fastholdt tidspunkt.

**Geopolitisk forsyningsrisiko:** Som de tre historiske tilfælde af vigende forsyning viser, har den hidtil største risiko for afbrudt/vigende forsyning i praksis været af geopolitisk natur, hvilken igen kan relateres til både politiske, sociale, regeringsmæssige, økonomiske og miljømæssige forhold. Ingen af de metoder til ressourcevurdering anvendt i LCA indtil nu har inkluderet geopolitiske aspekter. Denne pointe er værd at overveje i den videre udvikling af konsekvensvurderings-komponenten af LCA. I de mere nylige tilgange til vurdering af ressource kritikalitet, er den geopolitiske dimension inkluderet som en af indikatorerne, men altid i et statisk perspektiv, idet kvantificeringen af de to hovedindikatorer bag den geopolitiske vurdering, nemlig Herfindahl-Hirschman index (HHI) og worldwide governance indicators (WGI), altid gøres på basis af data for et specifikt tidspunkt. Dette PhD projekt har bidraget til at inkludere et mere dynamisk perspektiv på den geopolitiske forsyningsrisiko, ved at vise hvordan HHI kan blive væsentligt reduceret i fremtiden, dels ved øget genvinding, dels ved at ny minedrift udvikler sig mod at afspejle den globale fordeling af reserver.


Dette projekt har anvendt en meget bredere tilgang til følsomhedsvurdering i form af en teknologi-specifik vurdering og ved at se på muligheder for substitution ikke kun på element-niveau, men på alle niveauer af design/løsning fra det helt overordnede konceptniveau af en given teknologi/produktttype til det helt detaljerede komponent niveau. I den valgte direct-drive vindmølle case fandtes meget store substitutionsmuligheder, og alternative løsninger, der kunne frigøre designet fra afhængighed af Nd og Dy, fandtes på alle niveauer fra det overordnede generator design til det detaljerede valg af magneter. Ved at forstå analogien til risikovurdering blev det tydeligt, at en sådan teknologispecifik vurdering må anvendes for virkelig at forstå, hvor følsomt det vurderede system er for vigende forsyning af en ressource. Enhver anden tilgang kan let undervurdere, hvor let et system kan frigøres fra afhængigheden af en bestemt ressource gennem teknologisk udvikling og substitution. Denne tilgang vurderes endvidere realistisk for videre undersøgelse af dette studiums hovedspørgsmål, dvs. spørgsmålet om, hvorvidt ressource kritikalitet kan blive en begrænsning for den videre udvikling og fuldskala global implementering af grønne energiteknologier. I selv de mest avancerede fremtidige vedvarende energi scenarier anvendt i dette studium blev det fundet, at ud af de teknologier og sektorer, der vurderes at efterspørge Nd og Dy i fremtiden, står et fatefult for hovedparten af efterspørgslen. Inden for rammerne af et eller to PhD/post doc projekter, er det realistisk at udarbejde teknologispecifikke vurderinger af disse nøgleteknologier og dermed etablere en god forståelse for, om de er meget følsomme for vigende forsyning af bestemte ressourcer, eller om teknologiske substitutionsmuligheder kan findes lige så let for disse, som for her fundet for direct-drive vindmølle teknologien.
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Abbreviations

BAU  Business As Usual
DVD  Digital Video Disc
Dy   Dysprosium
EoL  End-of-Life
EU   European Union
Eu   Europium
Fe   Iron
GHG  Greenhouse gas
Gg   Giga gram (10^9 grams)
HDDs Hard Disk Drives
HDI  Human Development Index
HHI  Herfindahl-Hirschman Index
IT   Information Technology
kg   Kilo gram (10^3 grams)
LCA  Life Cycle Assessment
MFA  Material Flow Analysis
Mg   Mega gram (10^6 grams)
MRI  Magnetic Resonance Imaging
MW   Megawatt (10^6 watt)
MWh  Megawatt hour (10^6 watt hours)
Nd   Neodymium
NdFeB Neodymium-iron-boron
NLEV National Low Emission Vehicle
Pd   Palladium
PCB  Printed Circuit Board
PGMs Platinum Group Metals
PPI  Policy Potential Index
PPI-adjusted price  Producer Price Index-adjusted price
R&D  Research and Development
REEs Rare Earth Elements
REOs Rare Earth Oxides
Tb   Terbium
Tg   Tera gram (10^{12} g)
TWh  Terawatt hours (10^{12} watt hours)
WEEE Waste Electrical and Electronic Equipment
WGI  Worldwide Governance Indicators
WTO World Trade Organization
Y    Yttrium
Annotations/Definitions

Following is a list of relevant terminologies used within this thesis, and their definitions/explanations as intended:

**Geological Resource**: a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible (USGS, 2009a).

**Herfindahl-Hirschman Index (HHI)**: Herfindahl–Hirschman Index (HHI) is a widely accepted measure of market concentration, basically used to estimate the risk of putting all your eggs in one basket, i.e. the risk of dependency on monopolistic supply (U.S. Department of Justice, 2010).

**Human Development Index (HDI)**: the Human Development Index (HDI) is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. The HDI is the geometric mean of normalized indices for each of the three dimensions (UNDP, 2014).

**Life Cycle Assessment (LCA)**: is the approach to assess the environmental burdens of a product and/or process during its entire life cycle including raw material extraction, processing, distribution, use and final disposal (ISO 14040, 2006).

**Material Flow Analysis (MFA)**: is mapping the physical flows of resources into, through and out of a system defined in space and time (Brunner and Rechberger, 2004).

**National Low Vehicle Emission (NLVE) program**: in 1997, the U.S. Environmental Protection Agency introduced and voluntarily implemented the National Low Emission Vehicle (NLEV) Program, which got federally mandated in 2001. This law stressed on lowering the hydrocarbon emissions from automobile sector (USGS, 2012a).

**Native metals**: metals which exist in more or less pure/metallic form e.g. gold.

**Policy Potential Index (PPI)**: is a composite index, measuring the overall policy attractiveness of the jurisdictions (Wilson, 2013).

**Producer Price Index-adjusted (PPI-adjusted) price**: the Producer Price Index is a family of indexes that measures the average change over time in the selling prices received by domestic producers of goods and services. PPIs measure price change from the perspective of the seller. PPIs are used to adjust other economic time series for price changes and to translate those series into inflation-free dollars i.e. often known as PPI-adjusted price (U.S. Department of Labor, 2015).
**Rare Earths/Rare Earth Elements:** the rare earth elements (REEs), or just ‘rare earths’, are a group of 17 chemically similar metallic elements, including the 15 lanthanides (atomic number 57-71) plus scandium (atomic number 21) and yttrium (atomic number 39). The group is often divided into light rare earth elements (LREE) – elements from lanthanum (atomic number 57) to europium (atomic number 63); and, heavy rare earth elements (HREE) – elements from gadolinium (atomic number 64) to Lutetium (atomic number 71) plus yttrium (British Geological Survey, 2011).

**Resource:** within this thesis, it is used to refer to the mineral resources, in particular, metals that are extracted for use as feedstock in the anthropogenic supply chains.

**Reserve base:** is that part of an identified resource that meets specific minimum physical and chemical criteria related to current mining and production practices (USGS, 2009a).

**Reserve base$_{2009}$:** within this thesis, Reserve base$_{2009}$ refers to the amount of geological reserve base value in 2009 reported by the USGS (2009b).

**Reserve:** is that part of reserve base (part of the total geological resource of a metal) which could be extracted or produced economically at the point of determination (USGS, 2009a).

**Reserve$_{2011}$:** within this thesis, Reserve$_{2011}$ refers to the amount of geological reserve value in 2011 reported by the USGS (2011).

**Worldwide Governance Indicators (WGI):** the Worldwide Governance Indicators report on six broad dimensions of governance (voice & accountability, political stability and absence of Violence, government effectiveness, regulatory quality, rule of law, and control of corruption) for 215 countries over the period 1996-2013. The six composite WGI measures are useful as a tool for broad cross-country comparisons and for evaluating broad trends over time (World Bank, 2014).

**Specialty metals:** are those which are used in a product for their specific physical and chemical properties, and are used in small amounts. Their properties enable them to provide specific functionalities, making them crucial in many of the modern products (UNEP, 2011).
1. Introduction

The industrial revolution, starting in the 18th century followed by the exponential economic growth during the last two centuries, has been accompanied by a heavy reliance on fossil fuels, but also by a growing concern of their future scarcity along with the overwhelming global warming issue. The oil crisis of 1973 further highlighted the rising threat of future supply risk of fossil fuels (Bardi, 2014). The increasing concern of fossil fuels depletion has led the global society to devise other renewable means of energy and transport, to reduce dependency on the fossil fuels as well as to reach ambitious goals for meeting the climate change challenges of the future (IEA, 2014). This enormous transition from the current fossil based society to the future non-fossil society might, however, be constrained by the decreasing availability of other non-renewable resources such as metals – an issue that has been highlighted in several recent studies (c.f. Speirs et al., 2014; Elshkaki and Graedel, 2013; Moss et al., 2013, 2011; Hoenderdaal et al, 2013; Kleijin, 2012; Kleijin and Van der Voet, 2010; Kleijin et al., 2011; Andersson and Råde, 2001; Råde, 2001; Anderson, 2001).

The recent debate on potential resource constraints for the broad scale implementation of clean energy technologies in future has led to wider concern across the board. This concern, among others, lies behind growing research in the field of so-called resource criticality. According to many of existing studies related to this issue, critical resources can be defined as the ones that are both prone to high supply risk (high risk of future supply disruption) and imperative for a given system such as a technology, company, country, region, and the world. One of the pioneer studies on the topic was made by the National Research Council of USA (2008), where a two-dimension approach to assess resource criticality was presented to visualize the supply risk and importance of supply risk related to a number of resources for the US economy. The same matrix approach was adopted by the European Commission (2014, 2010) in order to identify the critical resources for the European economy. More recently, Graedel et al. (2012) have suggested a three-dimensional criticality space to reveal the resource criticality, where the additional dimension proposed is related to the environmental implications of mining.

A future non-fossil society needs to be built on emerging clean energy and transport technologies such as wind turbines, solar panels, electric cars etc. The existing state-of-the-art clean energy technologies such as the direct-drive wind turbines and electric vehicles use significant amounts of the so-called specialty metals such as rare earth elements (REEs) for the specific functionalities required. These specialty metals are relatively new in use compared to the major industrial metals such as aluminum, iron, copper, nickel and zinc etc. Nearly 80% of the total REEs production has occurred during the past twenty years (Graedel et al., 2014). Yet widely present in the earth’s crust, the rare earth’s supply challenge relates to their geological
occurrence in high enough ore grades to be mined economically (Habib and Wenzel, 2014; British Geological Survey, 2012, 2011). REEs have been classified as critical resources both by the European Commission and USA, due to supply risk being assessed as high and their importance judged as high in the modern high-tech applications (European Commission, 2014, 2010; Bauer et al., 2011, 2010; National Research Council, 2008).

Until now, there has been no significant recycling of these REEs from the end-of-life products (EoL) (Reck and Graedel, 2012; Graedel et al., 2011; UNEP, 2011). The recovery of REEs from the waste electrical and electronic equipment (WEEE) is quite challenging because it requires intensive dismantling if the source is complex products/components like electric motors found in a variety of modern equipment (Habib et al., 2014). On the other hand, the recovery of these REEs from the waste inherently will reduce the dependency on the primary supply (mining) and on imports from foreign countries such as China for the supply of REEs.

Estimating the recovery potential of critical resources from the existing and future waste flows is important to ensure their efficient recovery in future, and a precondition of this is detailed material flow analysis (MFA) of such resources in order to optimize the effort of such recovery initiatives. MFA has become a widely accepted tool for environmental, waste, and resource management and is defined as the systematic assessment of flows and stocks of materials within a system defined in space and time. A basic principle of MFA is the conservation of matter, where input is equal to output plus any change in stock (Brunner and Rechberger, 2004). MFAs were also applied on REEs and by using this, Du and Graedel (2011a, b) have provided preliminary estimates for the global stocks and flows of REEs, which is used as a baseline in the present work.

1.1. Objectives of this PhD work

The overall aim of this PhD study was to enhance the understanding of resource constraints for the emerging clean energy technologies in the future, using two REEs, namely neodymium (Nd) and dysprosium (Dy) as examples, and to reveal options for their recovery from waste flows. The overall aim can be broken down to the following objectives:

1. Explore resource constraints for the emerging clean energy technologies and the role of recycling in reducing such constraints with a focus on neodymium and dysprosium.

2. Devise a methodology and criteria to identify resources that are or can become critical to support society’s transition towards non-fossil technologies. Demonstrate the developed methodology on a selected clean energy technology.
3. Map and characterize existing and future waste streams focusing on their content of critical resources. Perform MFA of selected critical resources for Denmark.

4. Identify existing waste treatment technologies and highlight the drawbacks in the conventional waste treatment practices with respect to the recovery of critical resources from selected waste streams.

1.2. Content of the thesis

The structure of the thesis is as follows:

Chapter 2 describes the importance of metals for technology and mankind throughout history along with their scarcity and the resulting implications for society by exemplifying the three major resource supply disruptions (cobalt, palladium and REEs) during the past five decades. This chapter also provides an overview of the existing resource assessment approaches in the context of the current resource criticality debate.

Chapter 3 describes the key aspects of resource criticality assessment methodologies in detail with a focus on exploring the supply constraints of neodymium and dysprosium for the emerging clean energy technologies (Habib and Wenzel, I). This chapter briefly shows the role of recycling rare earths from the fluorescent lamps in meeting the future demand (Machacek et al., VI). The chapter also discusses the limitations of existing criticality assessment methodologies (Habib and Wenzel, II; Habib and Wenzel, III).

Chapter 4 presents the developed methodological framework for resource criticality assessment in a dynamic and technology specific perspective with the help of a direct-drive wind turbine case study (Habib and Wenzel, III).

Chapter 5 highlights the role of Material Flow Analysis in identifying the stocks and flows of critical resources and thereof estimating the recovery potential of such resources from the waste streams (Habib et al., IV). This chapter further presents the case study regarding tracking the flow of resources contained in the EoL computer hard disk drives to estimate the final recovery potential of resources (Habib et al., V).

Chapter 6 discusses the outcomes of this dissertation and explores the issues which can be of interest for future research.

Chapter 7 concludes the main findings of this dissertation.
CHAPTER 2

2. Mineral resources importance and scarcity – a brief history

Mineral resources have been generated as a result of geological events spanning over hundreds of millions of years and, thus, cannot regenerate within human lifetime. This finite nature of mineral resources makes them *non-renewable* by definition (Bardi, 2014; Tilton, 2003).

Mineral resources, in general, are categorized in three major groups: fuels – the minerals which are used for energy production e.g. oil, coal and natural gas etc.; metals – the minerals which are characterised by their specific physical and chemical properties such as their heat and electrical conductivity, strength, density, and malleability etc. Iron, copper, aluminium and gold are a few examples of metals; non-metals – the minerals which are used for industrial, construction and fertilizer production purposes such as sand, gravel, gypsum, phosphate rock etc. (Tilton, 2003).

Metals offer an interesting case to study regarding their long-term availability concern because they have been linked inextricably to societal development throughout the human history. This can be realised from the fact that the major societal development periods of human history have been named after metals such as the Bronze Age and the Iron Age (Wagner and Wellmer, 2009). Metals are not required *per se*, rather it is their specific physical and chemical properties, making them desirable to perform the specific functions in a variety of applications (Graedel et al., 2014; Wellmer, 2008). Thus, in principal, there is always a possibility of substituting a metal with another metal or material providing the same functionality in a specific application. During history, shortages of metals have motivated mankind to discover other more abundant metals which could provide the same functionality with even better performance.

Access to metals has been a consistent issue for mankind. Historically, there have been periods of metals scarcity due to various issues related to the nature of their availability and the variability and dynamics of these. Earlier, the major concern was the access to *native* metals – metals which exist in more or less pure/metalllic form. This was because the possibilities to separate metals from their ores were yet unknown to mankind. The only metals which were known to humans and were used in the Stone Age were the ones in their pure or metallic form e.g. gold, silver, copper and meteoric iron with high percentage of nickel (Bardi, 2014; Craig et al., 2011; Raymond, 1984). Gold was probably the first metal ever extracted and used by humans. This happened mainly due to relatively common availability of gold in the form of fine grains in alluvial deposits. The main use of gold in the Neolithic period was only for cultural purposes due to the limited access to pure gold (Bardi, 2014).

Copper in its metallic form also came into use around the same time period as gold. In contrast to the precious metals such as gold and silver which were used only for decorative and ornamental purposes,
copper was relatively hard and suited for the use in tools e.g. hammers and blades. However, these tools were much softer than the older tools made with stone in the Stone Age, though they provided the big advantage of not breaking into pieces when used with force. With time, the demand for native copper increased as multiple uses of copper were found, and soon there was shortage of native copper which forced humans to find other sources of copper. Meanwhile, the art of smelting copper from its ores e.g. malachite and azurite was most probably coincidentally discovered by the Neolithic man. The ancient humans probably learned the art of smelting from fireplaces and the pottery ovens, which might have been made of the rocks containing the copper ore. The intense heat together with some carbon fuel acting as a reducing agent provided the ideal conditions to separate metal from its ore. This was a great achievement in human history and led the foundation of early metallurgy (Bardi, 2014; Raymond, 1984).

The Copper Age was the first step towards more advanced metallurgy. Soon it was learnt that copper alone cannot be used in order to make more sophisticated metal tools. This was the beginning of the Bronze Age, where mankind discovered that copper and tin can be alloyed together to make a much harder alloy, called bronze. Apart from being harder than copper, this alloy had the melting point lower than each of the two metals. Thus it was easy for earlier craftsmen to melt and cast this alloy into desirable shapes. However, tin was much rarer than copper and demand of bronze was continuously increasing. This increasing demand forced humans to find far-off sources of tin, which led to the beginning of trade system in human history. This was, thus, the first time in history when mankind became dependent on foreign metal resources (Bardi, 2014; Craig et al., 2011).

The eventual transition from the Bronze Age to the Iron Age during 1200 to 1000 BC probably happened due to the supply disruptions of tin (Bardi, 2014; Cramer, 1995; Raymond, 1984). This may be the first indication of metal scarcity and its implications for a civilization, leading also to the first history of substituting one metal by another (Kleijn, 2012). Though iron is a much more abundant metal compared to any other metals used so far, it was tough for the earlier man to separate iron from ore because of its highly reactive nature towards atmospheric oxygen and higher melting point compared to copper and bronze. With the development of the right kind of furnace and providing the appropriate conditions, soon it was possible to produce metallic iron. The wider availability of iron and its hardness made iron the first choice of humans to make sophisticated tools on a large scale. Later, addition of little amounts of carbon to iron in order to make an alloy called steel proved to be a major step forward in metallurgy and thereof societal development (Bardi, 2014; Keijn, 2012; Raymond, 1984). Today, iron and its alloy steel are the most widely used metals (USGS, 2014).

In short, metals have played a significant role throughout human history. Earlier, the shortages of metals in their native pure/metallic form have paved the way to find other readily available metals which could
CHAPTER 2

substitute their functionality. In the recent history, the nature of supply shortages for metals has shifted from geological availability/scarcity to more geopolitical availability/scarcity. Geopolitical availability addresses the risk of potential supply disruptions caused by a single or few countries controlling the market of a particular metal and the level of political stability in such countries (see Chapter 3 for more details). The cobalt supply disruption in late 1970s, the palladium supply restriction in late 1990s, and the Rare Earth Elements (REEs) issue in 2010-2011 are good examples of geopolitical factor of metals supply risk. The following section provides the overview of cobalt (Co), palladium (Pd), and REEs supply disruptions.

2.1. Resource supply disruptions from the 1970s until present

2.1.1. The cobalt supply disruption in the 1970s

The cobalt supply restriction in 1978 is a good example of the limited availability of a metal due to supply disruptions, and the resulting outcomes/repercussions for society. Cobalt is a metal of strategic importance and is used in both industrial and defence related applications. The major uses of cobalt are superalloys which are further used in aircraft engines, magnets, cemented carbides, cutting tools and other chemical industry applications (Harper et al., 2012; USGS, 1999a). Cobalt has been pointed as a critical resource to the European Union due to the concerns related to its supply risk and economic importance (European Commission, 2014, 2010).

During the early 1970s, the Democratic Republic of Congo (then called Zaire) and the neighbouring country Zambia were in control of almost two third of the global cobalt production. The cobalt price had been relatively stable until 1975, when a series of events led finally to the cobalt crisis in 1978. In 1975 due to the civil war in Angola, the Benguela railway was closed which was the major export route of cobalt. Later, in 1978 there was political instability in the Democratic Republic of Congo when insurgents from Angola took control of parts of the Shaba province, where the major cobalt mines were located. This resulted in slowing down of mining activity. In spite of all these events, the Democratic Republic of Congo produced more cobalt in 1978 compared to the average yearly production during the previous years. However, the demand of cobalt increased sharply during the same time period due to an upsurge in the global economy. Thus, the gap between demand and supply coupled with the delayed transport of cobalt from the producing countries to the Western world resulted in price speculation. The price of cobalt increased fivefold from $11880 Mg⁻¹ in 1976 to $55000 Mg⁻¹ in 1979 (Alonso, 2010).

The supply constraints of cobalt had wide range implications for the industry and governments. This forced the stakeholders to find solutions such as reducing the use of cobalt, finding substitutes in key applications, diversifying the primary supply by increasing production of cobalt in other countries, and building stockpiles for defence related uses etc. Figure 2.1 shows the trend in price development and the change in consumption patterns of cobalt from 1964 to 1998. As a result of the crisis, the substitution possibility of cobalt was taken
very seriously, which is visible from the decreased consumption of cobalt in permanent magnets which were significantly displaced by the newly developed ferrite magnets. The total consumption of cobalt for permanent magnets dropped from 30% before the crisis to 10% after the crisis (Wagner and Wellmer, 2009). However, the use of cobalt increased for the superalloys during the same time primarily because of increasing demand from the jet engines industry as well as hardships in finding the substitute of cobalt in superalloys. Furthermore, the recovery of cobalt from the scrap superalloys also increased to twice (Alonso, 2010; USGS, 1999a).

The lessons learned and the initiatives taken after the cobalt crisis are still valid in the resource availability debate today e.g. the recent REEs issue. The cobalt supply disruption demonstrated the importance of having a more diverse supply of resources instead of a near monopoly situation, in order to eradicate or minimize the implications of potential supply disruptions for different stakeholders. Concerns over metals availability and supply disruptions have usually resulted in dramatic increase in the price of that metal. Immediately after the crisis, Zambia and Australia increased the production of cobalt to lessen the dominance of the Democratic Republic of Congo over global primary supply. The cobalt supply constraints also led the researchers and industry to find innovative ways to reduce and/or substitute the use of cobalt in primary applications e.g. permanent magnets, paints, ceramics and others. Further, it provided incentives to industry to increase the recovery rate of cobalt from the scrap material and, thus, reduce the dependence on primary supply. Moreover, the mining and refining companies improved their processes to reduce process losses and enhance the recovery of cobalt from its ores (Alonso, 2010). Very similar kind of initiatives can be seen after the REEs issue during the recent years, where the details can be found in next sections.

Figure 2.1: Demand of cobalt by various end-use sectors and cobalt price from 1959 to 1998 (adapted from Wagner and Wellmer, 2009; USGS, 1971, 1979, 1993, 1999a).
2.1.2. The palladium supply disruption in the 1990s

Palladium belongs to the precious metals group i.e. platinum group metals (PGMs), which are mainly used as catalysts in the automobile sector for pollution abatement. Other uses of PGMs are in fuel cells, petroleum refining, chemical industry, electronics, glass manufacturing, medical appliances, jewellery, and as investment (USGS, 2012a). The leading use of palladium is in automobile catalysts, which corresponded to almost 72% of total palladium consumption in 2013 (Cleantech VWS, 2014). In 1997, the U.S. Environmental Protection Agency’s introduced and voluntarily implemented the National Low Emission Vehicle (NLEV) Program, which got federally mandated in 2001. This law stressed on lowering the hydrocarbon emissions from automobile sector, and thus enforced the use of catalytic converters to reduce the vehicular emissions. This further led to an increased demand of palladium in catalytic converters for the gasoline-fueled vehicles (USGS, 2012a).

During the late 1990s, a supply disruption of palladium was experienced, because Russia in 1997 cut the exports of palladium by nearly 65%, while remaining the major producer with a 43% share of global palladium production. Meanwhile the demand for palladium had skyrocketed within the automotive industry (38% annual growth) due to the enactment of NLEV program in the same year.

![Diagram of palladium demand and price](image)

Figure 2.2: Demand of palladium by various end-use sectors and palladium price from 1980 to 2005 (adapted from Alonso, 2010).
The significant supply shortfall led to an enormous increase in the price of palladium from 1997 to 2000, which further resulted in dramatic changes in demand of palladium. The total demand of palladium in 2002 dropped by 50% compared to the demand in 1999. Even though the demand grew afterwards, it was still lower in 2007 compared to 1999 (Alonso, 2010; Johnson Matthey Precious Metals Management, 2008). Figure 2.2 reveals the demand side response to supply disruption and the resulting price increase. Another response from the demand side was to diversify the supply by increasing the production capacity in other countries such as Canada, South Africa and Zimbabwe.

2.1.3. The rare earths supply disruption during the recent years

The most recent example of metals supply disruption is of REEs. The REEs group consists of lanthanide series consisting of 15 elements (atomic number 57 to 71) plus scandium (atomic number 21) and yttrium (atomic number 39) (Kirk-Othmer, 2005; Ulmanns, 2005). They are often categorized into two categories based on their atomic weight, light rare earths (atomic number 57 to 63) and heavy rare earths (atomic number 64 to 71, and yttrium due to its chemical similarity with heavy rare earths). Their chemical similarity results in the occurrence of almost all REEs within a single rare earths bearing mineral in a host rock, though with varying concentration of individual REE. Due to the chemical similarity, these elements can be substituted with each other (British Geological Survey, 2011; Castor and Hedrick, 2006).

The term rare, which gives name to REEs, is in fact a misnomer, as these elements are widely present in the earth crust. The term refers to the historical difficulty of identification and refining of REEs, as the challenge of REEs supply relates to their geological occurrence in high enough ore grades to be mined and separated economically. REEs can be found geologically in more than 200 different minerals, however only a few minerals have sufficiently high concentrations of REEs to be mined economically at the moment (British Geological Survey, 2011, 2012; Kara et al., 2010).

REEs have unique physical and chemical properties which make them highly attractive in many of today’s high-tech applications e.g. permanent magnets containing neodymium and dysprosium. The performance level provided by these magnets in terms of their magnetic strength, thus, allows significant size and weight reduction in many of today’s modern applications while maintaining the same performance level. These magnets are widely used in computers, audio systems, electric and hybrid vehicles, cell phones, wind turbines, Magnetic Resonance Imaging (MRI) machines, and others (British Geological Survey, 2011; Du and Graedel, 2011b; Haxel et al., 2002; Hoenderdaal et al., 2013; Kara et al., 2010; Speirs et al., 2013a). Figure 2.3 shows the end-use sectors for REEs in general and the specific end-uses of neodymium and dysprosium.
Figure 2.3: The end-use sectors for REEs in 2013 (derived from Machacek and Fold, 2014), and the end-use product categories for neodymium and dysprosium in 2010 (adapted from Habib and Wenzel, I).

From 2005 to 2010, China has been the dominant producer with 97% share of the global REEs production. During the same period, the Chinese government kept shrinking the export quota of REEs to the rest of the world, where this quota had reduced by almost 53% from 2005 to 2011 with the most significant reduction from 2009 to 2010, which alarmed the industrial players and governments alike. Although, China had increased the export quota a little from 30.2 to 31 Gg in 2010, this however did not assure the relaxing of export quota during the years to come (see Table 2.1). Yet, to comply with the complaint filed by the EU, Japan and the US at the world trade organization (WTO) on the export-control measures imposed, in which China lost, the country changed export quota regulations to export licences in early 2015 (Investor Intelligence, 2015; World Trade Organization, 2015).

<table>
<thead>
<tr>
<th>Table 2.1: Chinese export quota of REEs from 2004 to 2012</th>
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<td>REEs (Gg year⁻¹)</td>
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Source: Lusty, 2010; Investor Intelligence, 2012

China has reduced the export of REEs to the rest of the world in order to prioritize the domestic demand, and to increase the production and export of high value goods using REEs e.g. permanent magnets, motors, and batteries. Due to the industrial and strategic measures taken by the Chinese government, the world market has experienced the ever highest prices of REEs in 2011, where price of neodymium oxide quadrupled to
$355 \text{ kg}^{-1}$ in July 2011 from $85 \text{ kg}^{-1}$ in 2010. The same trend can be seen for dysprosium oxide where the price got six times higher, from $350 \text{ kg}^{-1}$ in 2010 to $2200 \text{ kg}^{-1}$ in July 2011 (Buchert, 2011; Hoenderdaal et al., 2013). Figure 2.4 shows the price development of some rare earth oxides (REOs) from 2001 to 2015.

Figure 2.4: Development in price of rare earth oxides (REOs) from 2001 to 2015. The figure highlights the skyrocketed prices of rare earths in 2011 as a result of both the supply constraints imposed by China, and on the same time increasing demand of rare earths by the rest of the world (adapted from Buchert, 2011; Vestbø, 2015). Note that the price data for 2010-2011 are elaborated to show the details of rise and fall of the peaks.

This rapid increase in price led governments and industry to seek other solutions, including stockpiling, investing in mines outside China, replacing REEs by other elements, and increasing recycling rates (Machacek and Fold, 2014). Some recent studies have particularly focused on recycling of REEs (Binnemans et al., 2013; Chancerel et al., 2013) and on estimating the potential of recycling to meet the expected future high demand of REEs (Rademaker et al., 2013).

The immediate response to this supply disruption imposed by China was opening of new mines outside China and bringing REEs production online. This has led to reduce the Chinese share of global REEs production from 97% in 2010 to 87% in 2014. The remaining 13% is supplied by USA, Australia, India, Brazil, Malaysia, and other countries (USGS, 2013). This still gives REEs supply an alarmingly high score of 7,595 compared to 9,500 in 2010 (maximum 10,000) on the Herfindahl–Hirschman Index (HHI). Compared to this monopolistic supply situation, the Geological Reserves themselves are widely distributed in many countries, and the monopoly situation, therefore, could be reduced with adequate measures taken (Habib and Wenzel, 2014).

There are currently more than 200 on-going exploration projects outside China regarding REEs mining worldwide (Lusty, 2010; Merriman, 2013). These are initiated mostly by small and medium sized companies.
which often do not have sufficient cash flow of their own, and only a few out of these 200 projects will probably ever get to the production stage (Wellmer and Dalheimer, 2012). This is because of the possibility of very few projects being able to meet all the success criteria e.g.: ore grade of the resource, distribution of heavy and light REOs, access to labour and other necessary resources, technical and economic feasibility of processing plant, getting environmental approval, marketing plan and funding issue to reach the production stage. The overall process from exploration to the production of saleable products may take 5 to 12 years, which means that the few projects that fulfil all the criteria may still not be in a position to start production by 2015 (Kingsnorth, 2012).

2.1.4. Key lessons learned from the cobalt, palladium, and rare earths supply constraints

There are a number of lessons which can be learned from the above mentioned cobalt, palladium and rare earths crises:

- The underlying reason behind all the three resource crises has been of political nature, where the supply disruptions have been imposed by restraining the export to outer world by the dominant producing countries, and due to the political stability and governance issues of the producing countries.
- The immediate result of such a supply disruption has resulted into skyrocketed prices within a short time, which has forced the industry to cut short the demand of resource in question by looking for the opportunity to completely avoid or minimize the required amount of resource, and find other easily available substitutes.
- Another response has been increased investment by the stakeholders in research and development (R&D) programs to find the efficient recycling and recovery techniques of such resources from the waste streams.
- The other measures include enhancing the production capacity of existing facilities and opening of new mines in other countries than the dominant producers to diversify the supply, and thus reduce the risk of supply disruption in medium-to-long term future.
2.2. **Resource assessment approaches**

Due to the worldwide growing concern of decreasing resource availability resulting from increasing pressure on natural resources by growing population and increasing dependency on foreign supplies, resource efficiency has become a key element for sustainable development policies across the world (Fritsche et al., 2013; European Commission, 2011). Consumption of resources has been a concern in sustainability assessment since the beginning. To assess the sustainability of resource consumption, two widely accepted and implemented tools i.e. material flow analysis (MFA) and life cycle assessment (LCA) are in use for more than two decades. MFA is an approach which focuses on mapping the physical flows of resources in a given system defined in space and time. MFA is based on a material and energy balancing concept. Already in 1970s, MFA was used in the field of resource and environmental management (Ayres et al., 1985; Huntzicker et al., 1975; Kneese et al., 1970). As mapping the flows and stocks of critical resources is a prime objective of this dissertation, a whole chapter is dedicated to highlighting the role of MFA in resource management with a focus on critical resources (see Chapter 5).

Recent studies have provided an overview of different LCA methods highlighting the issue of various criteria for the assessment of Resource depletion (Klinglmair et al., 2014; Rørbech et al., 2014). Some of the earliest developed methods to assess the Resource depletion indicator in LCA were based on decreasing availability of Geological Resource in relation to annual extraction rates e.g. the Institute of Environmental Studies (CML), Leiden University method (Guinee and Heijungs, 1995; Van Oers et al., 2002) and the environmental design of industrial products (EDIP) method (Hauschild and Wenzel, 1998) have considered this use-to-availability ratios approach. A recent study by Schneider et al. (2014) has proposed to incorporate the anthropogenic stocks of metals to calculate the Resource depletion. Moreover, Vieira et al. (2012) have suggested taking into account the ore grade depletion as a parameter to assess Resource depletion.

Another set of methods address the decline of universal reserves of exergy as an indicator of Resource depletion e.g. the exergy method proposed by Finnveden and Östlund (1997), the cumulative exergy demand (CExD) method by Bosch et al. (2007), and the cumulative exergy extraction from the natural environment (CEENE) method by Dewulf et al. (2007). Other methodological approaches assess Resource depletion by considering the change in the amount of energy required to mine the future lower quality Geological Resources resulting from present consumption e.g. Eco-Indicator 99 (Goedkoop and Spriensma, 2001) and IMPACT 2002+ (Jolliet et al., 2003). A more recent method called ReCiPe developed by Goedkoop et al. (2009) addresses the issue of Resource depletion by analysing the marginal extraction costs of resources in future.

As mentioned above, the current practiced LCA methodologies assess the Resource depletion using mass or energy based indicators where a few of them address the economic issues to some extent. None of the
CHAPTER 2

mentioned methodological approaches considers the potential supply constraints resulting from socio-economic factors along the supply chain of resources such as supply concentration (monopoly of supply), trade barriers, economic and political stability of producing countries, substitution potential etc. – i.e. the issues historically seen to be behind supply disruptions in practice. To cut it short, current resource assessment methodologies in LCA address the depletion and to some extent the scarcity of resources, but none of them considers criticality as a whole (Van der Voet, 2013). The challenges and opportunities of incorporating criticality into the existing resource assessment methods in LCA has been extensively discussed in the recent attempt of European Commission to harmonize the methodological framework of resource assessment in LCA (Manicini et al., 2013). Moreover, Schneider et al. (2014) have suggested a more comprehensive methodological framework by addressing the economic aspects of resource depletion which are intended to complement the existing assessment models.

2.3. The debate on critical materials – a brief historical overview

The 20th century is remarkable in the whole human history as it has witnessed unprecedented economic growth rate and technological development. As an inherent consequence, it has also seen an unparalleled rate of mineral resources exploitation which has been an engine for this rapid economic growth as well as technological advancements. In fact, the amount of metals mined in the 20th century alone is more than the amount mined during the whole human history (Tilton, 2003). During the same century, there have been two world wars which resulted in massive destruction of infrastructure worldwide. Mineral resources, especially metals, have been in huge demand not only before and during these wars in order to manufacture all the weapons and war crafts, but also after the wars to rebuild the lost infrastructure and to develop new technologies (Kleijn, 2012; National Research Council, 2008).

To the best of the author’s knowledge, the term Critical materials was also used for the first time in context of World War II, where the Strategic and Critical Materials Stockpiling Act was introduced in 1939 to ensure a stable supply of strategic materials for defence and national emergency purposes (National Research Council, 2008). After the war was over, there was even more demand of a secure and stable supply of mineral resources, not only to rebuild the destroyed infrastructure, but also to achieve further industrial, technological, and economic growth (Kleijn, 2012).

In 1951, the U.S. president Harry S. Truman established the President’s Materials Policy Commission (Truman, 1951). This commission is more often called as the Paley commission, after the name of its chairman William S. Paley. The commission was formed to explore the Materials Problem and suggest ways by which private actions and public policies in the years ahead can help avert or overcome materials shortages which might threaten the long-run economic growth and security of the United States and other free nations. In June 1952, the commission prepared a comprehensive report called Resources for Freedom,
according to which the main causes of Materials Problem were: imbalance between soaring demands for materials and the means to satisfy those demands, depletion of domestic resources in other high consuming countries e.g. western Europe together with their weakening colonial ties, and the shift of focus of resource rich developing countries (especially former colonies) in becoming industrial states instead of materials export. The commission came up with three overarching suggestions: first, there should be a focus on getting more energy and materials from domestic resources (by pushing back the technological, physical and economic boundaries that presently limit supply); second, the burden of use should be shifted from scarcer materials to widely abundant materials; third, materials can be obtained from abroad on beneficial terms for the United States and the others (The President’s Materials Policy Commission, 1952).

The Paley commission’s report was well received by the public and private authorities, and in fact, it provided the basis for the United States policy regarding material’s security, which further led to stockpiling of strategic materials for the United States. Another outcome of the report was formation of the non-profit organization Resources for Future in 1952, named after the report prepared by Paley commission, and with Paley as its chairman. In 1963, Resources for Future published one of the most influential books called Scarcity and Growth by two economists (Barnett and Morse, 1963). Their purpose was to perform an empirical analysis to test the hypothesis of increasing natural resource scarcity in the United States for a period from 1870 to 1957. They collected the price data for minerals, agriculture and other renewable resources from 1870 to 1957, where it was found out that the price level of all natural resources has decreased overtime with the exception of forests. Linking the change in price level to increased availability/scarcity, it means that the availability of all the resources, except forests, had increased over the mentioned time period. Thus, the hypothesis of increased scarcity of natural resources could not find empirical support. The authors explained this increase in availability by technological developments which were credited for decreasing the extraction costs of resources and hence increasing the size of geological reserves (Barnett and Morse, 1963; Tahvonen, 2000).

In the debate of materials scarcity, the next influential step was the publication of one of the very famous, yet controversial, books The Limits to Growth by the Club of Rome in 1972 (Meadows et al., 1972). The authors of The Limits to Growth used System Dynamics as a tool to model the evolution of the global economic system for a time period of over a century. They modelled a number of different scenarios representing the dynamic interactions between five main factors of societal growth i.e. population growth, renewable and non-renewable resources, capital resources and pollution, and presented the resulting implications of such interactions on each of these sectors. The results they presented were far from optimistic as they showed depletion of resources coupled with deteriorating environmental quality by the middle of 21st century as a result of exponential population growth and increasing industrial activities (Meadows et al., 1972; Bardi, 2011). The timing of this study publication was just appropriate as in 1973 the first oil crisis happened,
which further strengthened the ongoing debate on resource scarcity. According to Kleijn (2012), *if there was ever a time that resource scarcity received wide public attention, it was then*. Although the study had been receiving huge criticism since its publication regarding its pessimistic results for resource depletion, recent studies found out that the past 30 years trend for parameters like population growth, pollution and resource depletion has been following, to large extent, the base case scenario presented in The Limits to Growth study (Bardi, 2011; Hall and Day, 2009; Turner, 2008).

By the end of 20th century, the widespread debate of long term mineral availability was subsided by other growing issues such as environmental degradation (Ayres, 1993; Kesler, 1994). This was also because no real scarcity happened during 80s and 90s, and in fact the price of several mineral commodities declined as a result of technology advancement which signalled growth in resource availability rather than increasing scarcity/declining availability. The concern that the environmental degradation and the resulting external costs would limit the availability of mineral resources replaced the fear of resource depletion (Tilton, 2003). Gavin Mudd and others have extensively worked in the past couple of years regarding quantification of environmental implications in the form of increased energy and water consumption along with increased mining waste generation per unit of metal production in a historical perspective for the Australian mining industry. They have clearly demonstrated that the environmental burdens are directly proportional to the decreasing ore grades, which has resulted in the past century due to increasing demand and thereof over exploitation of metals (Mudd, 2007a, 2007b, 2008, 2009a, 2009b, 2010; Mudd and Diesendorf, 2008).

During recent years, the debate regarding mineral resource scarcity/availability, especially of metals has renewed. However, the major concern this time is the long term availability of metals for the wider deployment of clean energy technologies such as wind turbines, electric and hybrid vehicles and solar panels etc., which are seen essential for a transition from the current fossil based society to a future low-carbon society. These technologies are important for not only reducing our dependency on non-renewable fossil fuels such as oil, coal and gas but also to save the environment from greenhouse gas (GHG) emissions by burning of fossil fuels, and hence to decrease the resulting global warming and its impacts in the future. The International Energy Agency (IEA, 2014) has developed a number of energy scenarios which offer the possible roadmaps to achieve the climate protection goals e.g. keeping the rise in global warming to 2°C above the global average temperature of pre-industrial times, set by the International Panel on Climate Change (IPCC, 2014). The required pace of this broad scale transition of current fossil based energy systems

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1 International Energy Agency (IEA) has a range of the so called BLUE scenarios which offer the potential energy roadmaps to meet the international target of keeping the global average temperature below 2°C relative to the pre-industrial temperature by stabilizing the atmospheric concentration of greenhouse gases at 450 ppm CO₂-eq. International Panel on Climate Change (IPCC) sees this goal as an imperative to avoid the irreversible and dangerous climate change. Detailed information of the climate change goals and different scenarios to avert this change can be found at IEA homepage (http://www.iea.org/publications/scenariosandprojections/) and IPCC homepage (http://www.ipcc.ch/).
to the future renewable based systems at a global scale to meet the climate protection goals entails significant dependency on raw materials such as metals. There have been recent studies published focusing on material dependency of clean energy technologies required for such a transition (c.f. Elshkaki and Graedel, 2013; Kleijn, 2012; Kleijn and Van der Voet, 2010; Kleijin et al., 2011; Andersson and Råde, 2001; Råde, 2001; Anderson, 2001). Moreover, the availability concern of specialty metals such as REEs for these clean energy technologies has gained wide attention, and this issue has been dealt at length in this dissertation (see Chapter 3).

Recently the term critical resources has, thus, resurfaced, though this time the term is used more in relation to reliability of minerals supply for the economy and emerging technologies in contrast to the earlier use of this term in 1931 in the context of securing the supply of strategic and critical resources for national defence purposes in USA. The term criticality in its current meaning along with the methodological approach to assess criticality of minerals has been first introduced by the National Research Council, USA (2008). The same study has defined critical minerals as those that are both essential in use and subject to considerable supply risk. Later, the European Commission also adapted the methodological concept with some alterations to identify the critical resources for European Union (European Commission, 2014, 2010). More recently, Thomas E. Graedel and his team at Yale University, USA have come up with the so far most comprehensive criticality assessment methodology for various societal levels e.g. global, national and corporate (Graedel et al., 2012). Although, there have been a number of studies which dealt with resource criticality assessment regarding wider implementation of clean energy systems in future, there has been a general lack of in-depth analysis of considering a technology in its design perspective (for details see Chapter 3). The question is whether criticality of resources for the emerging clean energy technologies can be reduced or completely eliminated by considering the various design alternatives available along the product design hierarchy, and this is elaborated on through a case study in a comprehensive and robust manner in this dissertation (see Chapter 4).
3. Key aspects of resource criticality assessment approaches

In the pioneering and probably the most influential study so far on resource criticality assessment (National Research Council, 2008), a resource is regarded as critical if it is subject to a risk of supply constraints, and on the same time, is essential in use. Thus, resource criticality has been mainly attributed to the assessment of two parameters i.e. availability and importance. Availability of resources is a function of several underlying factors depending on the defined scope and time horizon of criticality assessment activity. In short-to-medium time horizon, the availability concern is more of an institutional inefficiency nature delineated by market failure to cope with the changing circumstances. For example, availability of resources may be temporarily jeopardized due to factors, inter alia, enormous increase in demand, highly concentrated market, and weak legislative measures and/or lack of infrastructure to recover the resources from waste streams etc. In the long-term, resource availability is mainly a concern of physical constraints such as depletion of Geological Resource both quantity and quality wise (National Research Council, 2008; Alonso, 2010). Based on this argument, the European Commission has not included the physical availability parameter in its resource criticality assessment (European Commission, 2014, 2010).

The second major element of criticality assessment, importance is also dependent on several constraint parameters conditional to the system chosen. Taking a product as an example, a resource is selected mainly due to its pivotal role for the specific functionality required, for which no or only a few satisfactory substitutes are available given the technical and economic feasibility conditions. This denotes the high importance of a resource for a product. Yet, the resource under question will not be considered as critical if it is not facing any supply risk meanwhile. For a company, a resource may be of high importance if it is present in products representing a significant share of revenue generated. Furthermore, for a country or a region, the importance of a resource can be explained by its presence or role in the overall economic activity of that geographic region e.g. if a large share of population is associated with the production of that resource and/or products in which the resource is embodied (Graedel et al., 2012; National Research Council, 2008). Following is a brief explanation of key parameters considered to evaluate the availability and importance, and thereof criticality assessment of resources:

**Availability (Supply risk)**

**Short-to-medium term**

- **Global Supply Share** – commonly referred to as country concentration or global supply concentration, is an indicator to evaluate the supply risk originating from highly concentrated market e.g. the risk posed by only one or a few countries/companies controlling the supply of a resource. The notion behind using this indicator is that supply diversity enhances supply security. The Global Supply Share is usually estimated with the help of HHI based on either global supply or geological reserves share by countries. HHI can be calculated by using Equation 1:
KEY ASPECTS OF RESOURCE CRITICALITY ASSESSMENT APPROACHES

\[ HH1 = \sum_{i=1}^{N} \left( S_i^2 \right) \]  

(Equation 1)

Where \( S_i \) is the share of country \( i \) in the global primary supply of a resource and \( N \) is the number of countries.

- **Country Risk** – has been considered in most of the criticality assessment studies to reveal the potential supply disruptions based on the political stability and governance level of producing countries. Assumption here is that producing countries with dwindling political stability and poor governance impose high supply risk of resources. Country risk is mainly estimated with the help of worldwide governance indicator (WGI) developed by the World Bank (2014). Achzet and Helbig (2013) have mentioned some other indicators such as global political risk index (GPRI) (Eurasia Group, 2014), policy potential index (PPI) developed by Fraser Institute (Wilson, 2013), and human development index (HDI) developed by the United Nations (UNDP, 2014).

- **Significant demand growth** – an unexpected and significant increase in demand may lead to short-term imbalance between demand and supply, especially in situations where a resource is produced at maximum capacity and substantial stockpiling has not been accomplished previously.

- **Recycling rate** – the notion behind using recycling rate as one of the key indicator to evaluate availability of a resource is that the resources having high recycling rates are less prone to any supply disruptions compared to resources with low recycling rates.

- **Environmental and social aspects** – may cause supply disruptions of a resource in short-to-medium term future if environmental degradation and consent of local inhabitants are not considered appropriately.

**Long term**

- **Depletion time** – is considered an important indicator to assess the supply risk by estimating the time it takes to deplete the known geological reserves/reserve base. It is calculated as a ratio of reserve/reserve base to production. In most of the studies, depletion time has been estimated using a static approach where reserve/reserve base is considered as a static entity and is divided by present consumption rate, which thus provides only a glimpse of Geological Resource availability at one point in time. There lies, however, more realistic way to estimate the depletion time using dynamic approach which considers the growth in reserve/reserve base overtime along with the projected increase in demand.

- **By-product ratio** – indicates the share of a resource produced mainly as a by-product of a main metal such as REEs are mainly produced as a by-product of iron. The concept behind using this indicator is that the supply of resources produced as by-products is more risky, and fragile to changing
circumstances as their availability mainly depends on the availability of main product. This indicator is valid for both short-to-medium and long-term future.

- **Investment in mining operations** – is an important indicator to explore the resource constraints in long-term future, where the notion behind is that more investment in resource exploration and mining operations today would increase the mineral availability in future, as opening a mine and starting the mineral production might take 10-15 years.

**Importance (Vulnerability to supply risk)**

**Product and/or technology level**

- **Substitutability** – the importance of a resource in use can be indicated with a measure of its substitutability given the conditions of similar/equivalent functionality and performance. The resource which is easy to substitute with other resources in a specific use is less important for that particular application. Thus, the supply disruption of such a resource may not necessarily hinder the large-scale production of the particular application.

**Company level**

- **Share of revenue generated** – a resource or the product in which particular resource is embodied may be of pivotal significance to the profit generation and marketing of a company. Thus, the underlying concept here is that the revenue generated by a company may be severely impacted in an event of supply disruption of that particular resource.

**Country/region level**

- **Economic importance** – a resource may be of significant economic importance for a geographic region based on the number of people attached to the production of a resource or the products containing these resources. The rationale of considering this as an indicator is the overall economic impact caused by increasing unemployment due to closing of mines/companies producing resources/products respectively or vice versa.

The usual practice in criticality assessment studies so far has been to: first, evaluate the above mentioned indicators individually for each resource; seconds, weight them against each other; and finally aggregate their weighted scores to get the one final number for each, availability and importance dimensions of criticality assessment. Figure 3.1 shows the graphical representation of the criticality matrix approach applied in various studies to assess the resource criticality for different systems. Meanwhile, the figure also shows that all the mentioned studies have considered REEs as critical resources, especially for the clean energy technologies (Bauer et al., 2011, 2010). Since one of the aims of this dissertation is to explore the potential supply constraints of critical resources for the emerging clean energy technologies, the following
case study elaborates further on key aspects of potential supply risk assessment of REEs for the clean energy technologies along with the background uses.

Figure 3.1: Criticality matrix developed by three different studies where e.g. rare Earth Elements (REEs) are identified as critical resources due to their high supply risk as well as high importance for the system under investigation. REEs: Rare Earth Elements; Nd: Neodymium; Dy: Dysprosium; PGMs: Platinum Group Metals; Nb: Niobium; Al: Aluminium; Fe: Iron; Cu: Copper; Li: Lithium. Red solid lines in the upper right corner of these matrices indicate the threshold limit for resources to be considered as critical (adapted from Habib and Wenzel, III).

3.1. Case study I: Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling

In Habib and Wenzel (I), the growing concern with respect to risk of supply disruption of the two key REEs namely neodymium and dysprosium and the resulting implications for the wider implementation of clean energy technologies in the future has been explicitly addressed. The major use of these two elements is neodymium-iron-boron (NdFeB) magnets (Machacek and Fold, 2014; Buchert et al., 2011) which are the strongest permanent magnets developed so far (Dawson et al., 2014; Weichmann, 2009). NdFeB magnets are further used in various end-use products ranging from body care and home appliances, and information technology and telecommunication (IT & Telecom) to transport and energy sectors. The current state-of-the-art direct-drive wind turbine technology and the electric and hybrid vehicles are two major clean energy technologies which are as yet highly dependent on these magnets for the performance and size reduction benefits offered. Moreover, the demand of these elements for emerging clean technologies is expected to grow rapidly in the future (Alonso et al., 2012; Angerer et al., 2009). These factors together with the high supply risk imposed by the current near monopolistic market situation makes these elements particularly critical for the large scale deployment of clean energy technologies in future.

Several already published studies have evaluated the future development of renewable energy technologies and their resource constraints (Elshkaki and Graedel, 2013; Kleijn and Van der Voet, 2010; Moss et al., 2013, 2011). Although these studies provide very useful analyses of future energy systems and the associated material constraints, most of them have not simultaneously addressed the background development in other key sectors and the potential increase in demand of constrained resources by other end-users. Hoenderdaal et al. (2013) have considered this concern for dysprosium.
The case study presented here (Habib and Wenzel, I) has addressed the issue of possible future supply constraints of neodymium and dysprosium for the emerging clean energy technologies as well as other potential end-use sectors. This work offers a comprehensive and robust comparison of scenario dependent demand of neodymium and dysprosium with the primary and secondary supply by 2050. Moreover, this case study is the first to report the potential of recycling neodymium and dysprosium in lowering the geopolitical nature of supply risk (influence of recycling on HHI) together with reducing the risk of geological reserve depletion until 2100.

The aim of this case study has been to explore the risk of supply constraints considering the predicted high demand of neodymium and dysprosium and their forecasted supply on the shorter and longer term. To reach the aim, we have tried to answer the following questions:

i. *The scale of demand vs. supply:* how does the scale of the forecasted demand for neodymium and dysprosium by emerging technologies compare to the projected supply in a trend projection of mining?

ii. *The role of recycling:* how can recycling support the increasing demand and reduce the demand for mining?

iii. *The scarcity/depletion issue:* are we running out of neodymium and dysprosium resources, i.e. will available resources be depleted by increasing demands in a foreseeable future?

iv. *The supply bottleneck issue:* how rapid is the increase in demand – will supply be able to meet the pace of demand?

### 3.1.1. Methodological approach

As a framework for answering the above mentioned questions, four different future demand scenarios have been developed ranging from business as usual (BAU) to the ultimate renewable energy systems, not only for the wind turbines and electric and hybrid vehicles with two different battery technologies, but also for several background end-use sectors such as computers, audio systems, electric motors, and others. Likewise, a historical trend based projection regarding the primary production of neodymium and dysprosium has been formulated up to 2050 in order to reveal if the demand will outstrip supply. The demand in all the four scenarios has been further projected at a rather stable annual growth rate (0.5-1%) by 2100 to address the issue of lifetime/depletion time of geological Reserve\textsubscript{2011} of neodymium and dysprosium. Moreover, different recycling efficiencies for various end-use sectors have been assumed to investigate the contribution of secondary production to satisfying the demand of neodymium and dysprosium.

In Habib and Wenzel (I), and the other recent study regarding exploring the supply constraints of dysprosium for clean energy technologies (Hoenderdaal et al., 2013), the substantial demand of these elements by the conventional passenger vehicles is not considered – a major end-user of REEs particularly NdFeB magnets.
NdFeB magnets are used in almost 25 to 40 different electric motors present in passenger vehicles for several functions such as seat and seat belt adjustment, entertainment system, window lift and mirror adjustment, windshield washer, sunroof and headrest adjustment, door lock, automatic temperature control, power wheel steering, suspension system, and antenna lift etc. The electric and hybrid vehicles contain a main motor/generator system based on NdFeB magnets in addition to several small motors mentioned above. However, the majority of the studies have not considered this additional demand of NdFeB magnets by these small motors found in electric and hybrid vehicles (Hoenderdaal et al., 2013; Bauer et al., 2011, 2010). This yet unaccounted demand by the conventional as well as electric and hybrid vehicles is updated in this dissertation. This and other updates made to the work presented in Habib and Wenzel (I) are enlisted as follows:

i. Conventional passenger vehicles – according to Alonso et al. (2012), a conventional vehicle in developing countries is estimated to have 0.22 kg of REEs compared to a conventional sedan in North America consuming approximately 0.44 kg of REEs. In order to not overestimate the global demand of neodymium and dysprosium by conventional vehicles, it is assumed that 0.22 kg of REEs is representative of REEs demand by conventional vehicles worldwide. It is also assumed that this 0.22 kg of REEs is mainly used in NdFeB magnets found in different motors across the vehicle. Taking the average NdFeB magnet composition containing 29% neodymium and 2% dysprosium, this corresponds to 0.21 kg of neodymium and 0.01 kg of dysprosium per conventional vehicle.

ii. Electric Vehicles – the amount of neodymium and dysprosium required for small electric motors across the electric and hybrid vehicles is taken from Habib et al. (IV), which is equivalent to an additional demand of 0.33 and 0.023 kg of neodymium and dysprosium respectively on top of what has been already presented in Habib and Wenzel (I).

iii. Wind turbines – in Habib and Wenzel (I), conservative estimates regarding the amount of neodymium (150 kg MW$^{-1}$) and dysprosium (15 kg MW$^{-1}$) consumption by wind turbines are used. Whereas, in Habib and Wenzel (IV), the numbers are updated to 200 and 13.33 kg MW$^{-1}$ of neodymium and dysprosium respectively, based on actual data obtained from a leading wind turbine manufacturer.

iv. Lifetime of end-use products - in Habib and Wenzel (I) the lifetime of vehicles and wind turbines is considered to be 10 and 20 years respectively. However, the recent data presented in Habib and Wenzel (IV) reveals that the average lifetime of passenger vehicles and wind turbines is 16 and 25 years respectively, which has been updated in this dissertation.

3.1.2. Key findings

The above enlisted updates have resulted in considerably different results regarding the ultimate demand as well as secondary supply of neodymium and dysprosium in all the four modelled scenarios. The updated
results can be seen in Figures 3.2 and 3.3. Figure 3.2 shows a detailed overview of the projected demand and supply of neodymium in four different scenarios, where it becomes evident that the updated demand of neodymium reaches from 27 Gg year$^{-1}$ in 2007 to 145 Gg year$^{-1}$ in the Baseline scenario and 305 Gg year$^{-1}$ in the 100% REN scenario by 2050. These numbers are significantly higher compared to the results presented in Habib and Wenzel (I) where the results are documented as ‘‘The annual total demand of neodymium reaches from almost 16 Gg year$^{-1}$ in 2007 to approximately 100 Gg year$^{-1}$ in the Baseline scenario and 242 Gg year$^{-1}$ in the 100% REN scenario by 2050’’.

Figure 3.2: Comparative overview of forecasted future annual demand vs. the business as usual (BAU) projected primary supply and scenario dependent secondary supply of Nd in four different scenarios up to 2050. The bars show the forecasted annual demand and the slopes show the projected primary and secondary supply of Nd (adapted and modified from Habib and Wenzel, I).

Figure 3.3 shows a detailed overview of the projected demand and supply of dysprosium in four different scenarios, where it becomes evident that the updated demand of dysprosium reaches from 2.6 Gg year$^{-1}$ in 2007 to 13.6 Gg year$^{-1}$ in the Baseline scenario and 35 Gg year$^{-1}$ in the 100% REN scenario by 2050. These numbers are significantly higher compared to the results presented in Habib and Wenzel (I) where the results are documented as ‘‘annual total demand of dysprosium rises from nearly 1.8 Gg year$^{-1}$ in 2007 to approximately 11 Gg year$^{-1}$ in the Baseline scenario and 32 Gg year$^{-1}$ in the 100% REN scenario up to
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2050”. This higher demand in the updated results is mainly induced by the consumption of neodymium and dysprosium in the form of NdFeB magnets by the conventional as well as the electric and hybrid vehicles. Moreover, the updated results regarding secondary supply originating from recycling of EoL products show that the volume of neodymium secondary supply is estimated to reach up to 39 Gg year\(^{-1}\) in the Baseline scenario and 57 Gg year\(^{-1}\) in the 100% REN scenario. Similarly, the amount of dysprosium secondary supply is estimated to reach 3.5 Gg year\(^{-1}\) in the Baseline scenario and 5.8 Gg year\(^{-1}\) in the 100% REN scenario by 2050.

![Figure 3.3: Comparative overview of forecasted future annual demand vs. the business as usual (BAU) projected primary supply and scenario dependent secondary supply of Dy in four different scenarios up to 2050. The bars show the forecasted annual demand and the slopes show the projected primary and secondary supply of Dy (adapted and modified from Habib and Wenzel, I).](image)

The updated results presented in Figures 3.2 and 3.3 show a supply deficit from 2007 until recent, whereas no such supply shortfall has been realized in reality. This can be mainly attributed to huge uncertainties lying on both demand and supply sides. On the supply side, the increasing illegal mining, sales and export of REEs from China as a result of Chinese government policy on restricting the exports to rest of the world have never been documented in official statistics (Machacek and Fold, 2014; Kingsnorth, 2010). On the demand
side, there lays still a wide knowledge gap regarding the actual consumption of neodymium and dysprosium in various end-use products across the globe – an issue that has been highlighted in Habib et al. (IV).

The key findings of this case study can be grouped into following four points answering the questions raised in section 3.1:

1. The historical trend based projected primary supply of neodymium and dysprosium does not seem to be enough to meet the forecasted future high demand in all of the four scenarios. This imbalance between the forecasted demand and the BAU trend based projected primary supply can be counteracted in several ways such as:
   i. By increased pace of opening new mines
   ii. By increased recycling – the effect of this measure is, however, delayed by the lifetime of products in which neodymium and dysprosium are used
   iii. By technological substitutions, i.e. the future demand scenarios are established based on knowledge regarding resource dependency in present technologies – this may/will change in future.

2. Neodymium and dysprosium recycling is not able to reduce the demand for virgin neodymium and dysprosium significantly in the short-to-medium term due to the relatively long lifetimes of end-use products, which delays their appearance in waste stream for the final recovery of resources. However, recycling is found to play a major role in reducing this gap in the long term, i.e. beyond 2050. In Habib and Wenzel (I), recycling is also found to play a significant role in lowering the geopolitical aspect of supply risk (estimated based on the HHI) from 7,595 to 1,244 for neodymium and from 9,647 to 1,801 for dysprosium in the ultimate renewable energy scenario by 2100. This is foreseen mainly because of the increasing secondary production and thus the diversification of REEs supply (both primary and secondary) originating from a number of different countries in the future.

3. With respect to the available geological reserves of neodymium and dysprosium, our results have shown that the depletion of these reserves is not a concern for several hundred years ahead. In case of neodymium, only 30% of the currently known reserve is likely to be depleted by 2050 and for dysprosium only 40% of the reserve will deplete by 2050 even in the ultimate renewable energy scenario. Moreover, taking the role of recycling into account, our results indicated that the share of the Reserve_{2011} depleted by 2050 is only 15% for neodymium and 30% for dysprosium. Further, taking the historically proven developments in metal reserve estimates as being analogous for REEs, geological reserves of neodymium and dysprosium will not deplete for many hundred years ahead.
4. The supply risk issue of neodymium and dysprosium is found to be a bottleneck issue of opening new mines at an accelerated rate to satisfy the future high demand in the period from now until 2050. Our results indicate that the potential mining projects outside China do not have high content of dysprosium as China possess around 70% of the currently known dysprosium reserves. This suggests that China is very likely to play its dominant role for dysprosium primary supply in the short-to-medium term future until recycling provides significant secondary supply to reduce the contribution of mining in order to meet the future demand.

3.2. Case study II: Recycling of rare earths from fluorescent lamps

In Machacek et al. (VI), the role of future recycling in closing the loop of rare earths contained in the fluorescent lamp phosphors is explored. The phosphor powders of fluorescent lamps use three heavy REEs namely europium (Eu), terbium (Tb), and yttrium (Y). The average lifetime and efficiency of these lamps is about four times higher compared to the incandescent lamps. These lamps are expected to phase-out the majority of less efficient incandescent bulbs within the short-term future as a result of policy measures taken in different parts of the world to save energy (UNEP, 2014).

There are different types of fluorescent lamps such as compact fluorescent lamps (CFLs), linear fluorescent lamps (LFLs), and light emitting diodes (LEDs). LEDs offer a clear advantage over the other two types by using significantly lower volume of rare earths (Castilloux, 2014; Wu, et al., 2014) with potentially little or no terbium, and it is expected that majority of the future market share will be dominated by LEDs.

Figure 3.4a shows the forecasted market share of different lamps from 2015 – 2020. Figure 3.4b presents the secondary supply originating from three different modelled end-of-life recycling rate (EoL-RR) scenarios in the context of forecasted demand of europium, terbium and yttrium by the three energy-efficient lamp types jointly with anticipated primary supply of these REEs (details can be seen in Machacek et al., VI).

The results have shown that in 2015, the BAU scenario of 7% EoL-RR of the three REEs phosphors can fill the demand gap with about 7% and can account for up to 9% in 2020. In contrast, and most significant, is the ambitious scenario of EoL-RR of 53%, which enables a secondary supply of the three REEs phosphors of more than half of the demand by phosphor based lamps in 2015 and almost three quarters of demand by these lamps in 2020, and thus competes directly with primary supply. This study emphasizes the choices that our societies face regarding REEs supply, namely whether we would like to enable secondary REEs supply which has the advantage that it provides REEs as input that are already of much higher purity as compared to REEs from mining. Such a choice requires putting measures into place that foster higher EoL lamp collection rates, and higher REEs phosphor recycling rates. Machacek et al. (VI) have explored the hindrances to secondary supply, with a particular focus on valuing these resources.
3.3. An analytical review of existing criticality assessment methodologies

The concept of resource criticality assessment, as it has been used till now, has analogies to the traditionally used concept of risk assessment. In the risk assessment of e.g. chemicals or chemical production & storage facilities, the probability or risk of an incident to happen causing releases of hazardous substances and exposure to recipients is assessed (Glöser et al., 2015). The risk assessment, thus, comprise two dimensions, the first being the probability of an incident/release, the second being the consequence such an incident/release can have. The two dimensions of the existing methodological approaches to resource criticality assessment are analogous: the first being the assessment of the probability/risk of a disruption in resource supply, the second being the importance of such a disruption or the vulnerability of affected technologies or systems/economies to such a disruption.
The majority of resource criticality assessment studies have relied on the two main dimensions i.e. 
*availability* (supply risk) and *importance* (vulnerability to supply risk/importance of supply risk) by applying 
composite indicators to each of them, which in turn further consist of a number of sub-indicators. The choice 
of sub-indicators and their aggregation into one main indicator/dimension differs from study to study. For 
example, the substitutability parameter is part of supply risk dimension in the EU methodology whereas it is 
part of the importance/ vulnerability dimension in the methodology proposed by Graedel et al. (2012). Apart 
from these two most commonly used indicators/dimensions, the methodological approaches also differ on 
the *modelling assumptions/parameters*, including assumptions on the rate of recycling, the future growth in 
demand, unexpected demand by future innovations, etc. Further, the applied sub-indicators are often 
aggregated in an inexplicit and subjective manner. Habib and Wenzel (III) have presented an overview of 
the assessment methods and indicators of resource criticality studies which can be seen in Table 3.1.
<table>
<thead>
<tr>
<th>Study/Methodology</th>
<th>Geographical focus and System under study</th>
<th>Time horizon and Basic concept</th>
<th>Criticality indicators</th>
<th>Modelling assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graedel et al. (2012)</td>
<td>Global, National and Corporate</td>
<td>1-100 years, Criticality space having 3 dimensions: Supply Risk, Vulnerability to Supply Restrictions and, Environmental Restrictions</td>
<td>Geological availability, Geopolitical availability, Environmental Risk</td>
<td>Expected future demand growth</td>
</tr>
<tr>
<td>European Commission (2010)</td>
<td>Regional (EU)</td>
<td>10 years, Criticality matrix with 2 dimensions: Supply Risk and Economic Importance</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>National Research Council (2008)</td>
<td>National</td>
<td>10 years, Criticality matrix with 2 dimensions: Supply Risk and Impact of Supply Restriction</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>U.S. Department of Energy (Bauer et al., 2010)</td>
<td>Global, Clean technologies</td>
<td>0-15 years, Criticality matrix with 2 dimensions: Supply Risk and Importance to Clean Energy</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>U.S. Department of Energy (Bauer, et al., 2011)</td>
<td>Global, Clean energy technologies</td>
<td>0-15 years, Criticality matrix with 2 dimensions: Supply Risk and Importance to Clean Energy</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Duclos et al. (2010)</td>
<td>Corporate (General Electric)</td>
<td>NA, Criticality matrix with 2 dimensions: Supply and Price risk, Impact on General Electric</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
### Key Aspects of Resource Criticality Assessment Approaches

<table>
<thead>
<tr>
<th>Source</th>
<th>Scope</th>
<th>Timeframe</th>
<th>Methodology</th>
<th>Criticality Assessed for</th>
<th>Supply Risk</th>
<th>Importance/Vulnerability</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oeko Institute (Buchert et al., 2009)</td>
<td>Global, Clean technologies</td>
<td>5 years - 2050, Prioritization of critical resources against Supply risk, Rapid demand growths and Recycling restrictions, then summarized according to urgency regarding timeline</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>British Geological Survey (2012)</td>
<td>Global</td>
<td>2012, Supply Risk Index</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Oakdene Hollins (Kara et al., 2010)</td>
<td>Global</td>
<td>Unspecified long term, Criticality matrix</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Moss et al. (2011)</td>
<td>Regional (EU), Strategic Energy Technologies</td>
<td>2010-2030, Supply-chain Bottleneck Index</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Nieto et al. (2013)</td>
<td>National, Petroleum refining</td>
<td>NA, Criticality Index</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Geo and Gaustad (2014)</td>
<td>National, Photovoltaics</td>
<td>NA, Multi-metric approach</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Roelich et al. (2014)</td>
<td>National (UK), Low carbon electricity system</td>
<td>2012-2050, Dynamic material criticality</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

The classification of different indicators into supply risk, importance/ vulnerability to supply risk and others do not follow the same pattern in the respective studies. (adapted from Erdmann and Graedel, 2011; Speirs et al., 2013b; Habib and Wenzel, III).
CHAPTER 3

The different methodological approaches presented in Table 3.1 address relevant aspects of resource criticality assessment. However, as mentioned above, quantifying and aggregating the indicators in order to facilitate comparisons and prioritizations in decision making is not straight forward scientifically, and most studies have had to rely on assessing the parameters qualitatively and then subjectively weighting and aggregating these indicators to reach the final score, something that has attracted criticism (Bradshaw et al., 2013; Buijs and Sievers, 2011; Buijs et al., 2012).

According to Bradshaw et al. (2013), a mineral in itself cannot be critical by definition, as criticality is a situation/condition of the system under study due to some property leading to criticality. Thus, criticality is a dynamic instead of static phenomenon which is subject to change over time. This is also because the indicators used to assess criticality are dynamic in nature, such as:

- The reserve to production ratio, because geological reserves/reserve base of a mineral resource are not static entities but are subject to growing over time as a result both of new mine discoveries and of improved economic feasibility due to increasing market prices as well as the development of modern technology capable to efficient mining from low grade ores etc. Habib and Wenzel (I), thus, illustrate the historical development of reserve estimates showing a constant growth of estimated reserves of mineral resources such as iron (Fe), copper (Cu), Rare Earth Oxides (REOs), gold (Au) and silver (Ag) (see Figure 3.5).

- The global supply share, which is currently measured with the help of HHI also changes over time due to the continuous trend of opening new mines around the world and the derived change in global

![Figure 3.5: Development in geological reserve estimates and cumulative production for different mineral resources from 1996 to 2013 (adapted from Habib and Wenzel, I).](image)
supply share from countries producing mineral resources. This trend is also documented in recently published studies (c.f. Buijs and Sievers, 2011). Moreover, Habib and Wenzel (I) have shown that the global supply share is significantly influenced by recycling, as the resource recovery from EoL products containing the resource in question kicks off and gains a significant share of the world supply.

In Habib and Wenzel (II) the historical HHI trend with respect to the primary supply of different elements across the periodic table is explicitly presented, where it can be seen that HHI score has been changing for all the metals over the past two decades.

Figure 3.6: Development in HHI score of various metals from 1994 to 2013 and the estimated HHI score in 2050 (adapted from Habib and Wenzel, II).

In Figure 3.6, apart from showing the historical HHI trend of different metals estimated based on the primary supply from 1994 to 2014, the estimated HHI score for 2050 is also shown based on the assumption that the presently known geological reserves share of metals by countries is representative of future primary supply.
CHAPTER 3

by 2050 – an assumption which is subject to change depending on potential Geological Resource discoveries in future and/or changing economic and political circumstances.

- The *worldwide governance indicator (WGI)* is also updated every year by the World Bank as a result of changing political conditions in different countries around the world.

The majority of the studies mentioned in Table 3.1 have performed a *static* criticality assessment, which means that the results shown in these studies present the assessed criticality of resources at one specific point in time. As argued above, however, criticality should rather be seen in a more *dynamic* perspective since most of the indicators used to assess criticality are dynamic in nature and change over time. This suggests that the resource criticality assessments should be updated from time to time and preferably also forecasted by looking at scenarios for the future; because it will enable different stakeholders to have a longer term overview of issues related to resources as well as monitor the progress of any initiatives taken to reduce criticality.

Furthermore, the approaches used to assess the impact of a shortfall in supply on the economy of the concerned system is also receiving criticism (Buijs and Sievers, 2011). A good example is the assessment of the specialty metals which can be essential to a technology, but still used in very small quantities, and hence contribute insignificantly to the overall cost of the product. In such cases, an unexpected price hike for these speciality metals is often not likely to result in significant overall production cost increase or in any significant rollback of the overall technology.

Finally, we argue that the majority of the criticality assessment studies mentioned in Table 3.1 have considered the importance of supply risk or the vulnerability to supply risk dimension of resource criticality in a too general manner. Especially, the assessment of the substitutability of a given resource can in our view benefit from a more specific and technology oriented perspective. Often, substitutability is assessed at the elemental level, i.e., substitution of one element by another based on key physical and chemical properties of the element as such, e.g. substitutability of copper by silver or aluminium based on their conductivity properties or the like, and mainly qualitatively assessed based on expert judgments. We argue that assessing the vulnerability of being dependant on a specific resource including the options for, and ease of, substituting one resource by another, needs a more comprehensive assessment. Such an assessment should rely on a holistic understanding of product and technology development, and address ways to substitute not only the elemental resource as such, but the complex technological solutions to creating the features and functionalities of the products and systems of concern. We aim to illustrate and exemplify this point in the next chapter with the case study of direct-drive wind turbine technology – a technology for which REEs contained in NdFeB magnets are considered critical resources.
4. Criticality assessment in a dynamic and technology specific perspective

Chapter 3 has presented a detailed overview of key aspects for resource criticality assessment methodology where section 3.3 has extensively discussed the shortcomings of existing methodologies with respect to both the supply risk and vulnerability to supply risk dimensions. As a continuity of the previous chapter, the present chapter is aimed at presenting a methodological framework for resource criticality assessment in a dynamic and technology specific perspective.

4.1. Case study of direct-drive wind turbines

4.1.1. Methodological approach

In Habib and Wenzel (III), the identification and comparison of design alternatives for the direct-drive wind turbine are presented, here shown in Figure 4.1, where the same functionality is ensured (see Table 4.1).

Figure 4.1: A hierarchical product design tree of wind turbines illustrating design alternatives from bottom to top. An analysis of the feasibility of design substitutions at each level forms the basis of assessing the vulnerability to risks of resource supply constraints (dark blue boxes show the reference product i.e. the direct-drive turbine design assessed in the current study, light blue boxes show the design alternatives assessed in the current study, and the grey boxes show other design alternatives which are not considered in the current study) (adapted from Habib and Wenzel, III).
For example, as shown in Figure 4.1, in the current case study of wind turbines, the Component Level of the design tree presents two alternatives of the permanent magnet: REEs magnet uses neodymium and dysprosium, whereas the ferrite magnet is independent of REEs, but at the cost of additional iron consumption along with strontium (Sr) consumption to deliver the same functionality at the same performance level, resulting in the overall increased size of the ferrite magnet. Also derived alterations in the full product system perspectives must be included. In the mentioned case of magnet alternatives, the bigger size and weight of the ferrite magnet implies that the nacelle of wind turbine must undergo some design alterations. Once the design of the main component (the nacelle in this case of wind turbine) has been altered in order to accommodate the component level substitute, other structural implications may be further necessary, i.e. the overall size and weight of the nacelle may consequentially imply an increase of the size of tower requiring more steel to carry the nacelle. Such whole-system holistic consequences should always be followed to the end.

Since the case of the current study is direct-drive wind turbines, we have selected neodymium, dysprosium, copper, iron and strontium from a wide array of metals used in a wind turbine to illustrate our approach and to capture some of the key resource trade-offs when comparing alternative designs. Data regarding resource consumption of the selected resources was collected with the help of a wind turbine manufacturer, and Table 4.1 presents this actual resource trade-off between the available substitutes at all the four levels of product design tree.

As Table 4.1 illustrates, several options for releasing the wind turbine technology from its dependence on neodymium and dysprosium exist, each of course having in turn other dependencies. The data platform established in Table 4.1, however, allows for a supply risk assessment of each of the alternative designs, and it thus constitutes a platform for decisions on the character of resource dependency built into the product technology. This study shows the dynamic aspect of criticality assessment by developing a future demand...
scenario for the selected metals for the direct-drive wind turbine case study, where the potential future demand of selected metals by direct-drive wind turbines as well as all the other end-use sectors is taken into account. For this purpose the so-called *Blue MAP scenario* is selected, where the resulting demand of neodymium and dysprosium by all the end-use sectors is adapted from Habib and Wenzel (I). The future estimated demand of iron, copper and strontium until 2050 as well as the resulting secondary supply is explained in detail in the supplementary material of this study (see Appendix B).

Table 4.2: Overview of the Blue MAP scenario with estimated share of wind power produced by direct-drive wind turbines in 2050

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total Global Electricity demand (TWh)</th>
<th>Share of renewable (%)</th>
<th>Share of wind power (%)</th>
<th>Wind power demand 2050 (TWh)</th>
<th>Wind turbine market penetration rate of direct-drive turbines by 2050 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue MAP</td>
<td>40,137</td>
<td>48</td>
<td>12</td>
<td>4916</td>
<td>30</td>
</tr>
</tbody>
</table>

Adapted from Habib and Wenzel (I)

In order to determine the criticality of resources for the direct-drive wind turbine technology, the supply risk dimension of criticality is assessed quantitatively for all the here illustrated alternatives (see Figure 4.1 and Table 4.1) applying two supply risk indicators, namely geological availability and geopolitical availability. The geological availability has been estimated by taking into account the depletion of Geological Resources using two different geological reserve estimation approaches: first, a static reserve approach where the geological reserve of 2011 for all the resources considered in this study is assumed to be static, meaning that geological reserve does not grow over time resulting from any new discoveries or economic reasons; second, a dynamic reserve approach where the currently known reserves are assumed to grow over time until 2050. In the dynamic reserve approach, reserve growth is projected until 2050 using two different ways: first, by 2050 the current known geological reserves are projected to follow a historical growth pattern from 1994 to 2014; second, the currently known geological reserves are projected to grow up to the reserve base 2009 estimates provided by the U.S. Geological Survey by 2050 (USGS, 1996, 1997, 1998, 1999b, 2000–2008, 2009b, 2010, 2011, 2012b, 2013, 2014).

In order to estimate the geopolitical availability of resources, the HHI is used. The current level of geopolitical supply risk is calculated based on the global mine production, whereas the future HHI by 2050 is calculated based on the share of geological reserves located in different countries. In order to visualize the role of recycling in lowering the geopolitical supply risk, the future HHI estimation for neodymium and dysprosium includes the secondary supply originating from recycling of EoL products as well. The details regarding lifetime of various end-uses and their EoL recycling rates for all the resources considered in this study can be found in the supplementary material for Habib and Wenzel (III) (see Appendix B).
4.1.2. Key findings

The results presented in Habib and Wenzel (III) highlight that the reference design case of direct-drive wind turbine with permanent magnet generator containing NdFeB magnet is not likely to face neodymium and dysprosium supply constraints due to depletion of Geological Resources by 2050 considering the Blue MAP scenario. The amount of remaining geological Reserves_{2011} after considering the cumulative demand of neodymium and dysprosium by the reference wind turbine design case and the background end-use sectors by 2050 is estimated to be more than 80%, thus posing no geological supply disruptions in medium-to-long term future (see Figure 4.2). On the other hand, the reference direct-drive wind turbine case is currently facing geopolitical supply risk due to the present REEs market mainly dominated by one country i.e. China. However, this risk is subject to reduce significantly in the future due to opening of new mines outside China as well as increased recycling of EoL products (see Figure 4.3).

![Figure 4.2: Comparative reserve depletion estimates of neodymium, dysprosium, copper, iron and strontium for the present state-of-the-art direct-drive wind turbine design in the Blue MAP scenario, by considering the currently known static as well as projected future reserve estimates by 2050 (adapted from Habib and Wenzel, III). Note that the figure presents the resource demand in both the wind turbine and the background uses.](image)

Substituting this reference design case with alternative NdFeB magnet composition offers no significant efficiency trade-off as both alternatives provide the same function output per installed capacity. This further suggests that except the small resource trade-off regarding neodymium and dysprosium between both design alternatives (see Table 4.1), there is no additional mineral resource required to switch from one design option to the other. As there is no difference in the weight of NdFeB magnet used in both design options, indicates
that there are no further implications regarding the design and structural aspect of wind turbine. Furthermore, switching from the reference NdFeB magnet composition to the alternative NdFeB magnet composition adds no significant benefit to the overall supply risk of REEs for direct-drive wind turbines as these wind turbines are responsible for only 7 and 4% of the total neodymium and dysprosium demand respectively by 2050. Nevertheless, switching from the reference design case to this alternative design option does offer the benefit of reduced geopolitical supply risk for the wind turbine manufacturers due to less consumption of dysprosium, where 99% primary supply still originates from China.

Moving one step higher along the product design tree (see Figure 4.1) i.e. Component level, allows us to substitute the reference permanent magnet generator containing NdFeB magnet with a ferrite magnet. Furthermore, as shown in Table 4.1, this substitute is less efficient compared to the reference design case. In order to compensate this performance loss, a clear resource trade-off can be seen among both of the design options (see Table 4.1), where the NdFeB permanent magnet generator is dependent on neodymium and dysprosium whereas the ferrite magnet generator consumes a significantly larger amount of iron in addition to strontium. This performance enhancement of the ferrite magnet generator further leads to risk of design alteration in the nacelle of wind turbine followed by structural implications. The design risk primarily arises due to significantly large weight and size of the ferrite magnet leading to technical design alterations in the generator. Regarding the geological supply risk of choosing the ferrite magnet generator, the Reserve\textsubscript{2011} for

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Figure 4.3: The estimated historical and future Herfindahl Hirschman Index (HHI) of Rare Earth Elements (REEs), neodymium, dysprosium, copper, iron and strontium from 1994 to 2050. The HHI score of REEs has been differentiated between neodymium and dysprosium from 2013 onward. Moreover, the dashed trend line for strontium after 2013 reveals the data limitations regarding strontium reserves (adapted from Habib and Wenzel, III).
strontium seems to be already depleted by 2033 in the Blue MAP scenario even without considering the consumption of strontium by the ferrite magnet design alternative for direct-drive wind turbine (see Figure 4.2). This indicates a warning of potential supply constraints of strontium to the wind turbine manufacturers. On the other hand, using the dynamic reserve approach (Reserve base2009 approach) reveals that the amount of strontium reserve available by 2050 is subject to grow by almost a factor of 2 by 2050 compared to Reserve2011, instead of getting depleted as in case of static reserve approach. Moreover, according to the U.S. Geological Survey, the total resources of strontium are more than 1 billion tons, equivalent to 147 times higher than the current identified reserves (USGS, 2015). This means that the depletion of strontium reserves is not realistic at least in the foreseeable future. On the other hand, substituting the NdFeB magnet with the ferrite magnet would offer substantial benefits to the turbine manufacturers regarding the geopolitical supply risk as the supply of strontium is considerably wider distributed geographically compared to REEs (see Figure 4.3).

Switching from the permanent magnet generator with NdFeB magnet to the electrical excitation generator while retaining the direct-drive design offers a substantial resource supply risk trade-off (the Sub-assembly level of the product design tree shown in Figure 4.1). According to the data presented in Table 4.1, it becomes clear that the electrical excitation generator is 6% less efficient compared to the NdFeB permanent magnet generator. This leads to enhancing the installed capacity of direct-drive wind turbine from 1 MW to 1.07 MW in order to produce the same annual electricity output. This capacity enhancement further leads to the resource trade-off between both design substitutes as electrical excitation generator, though not equally efficient as the permanent magnet generator, avoids any REEs consumption, however, at the cost of extra iron and copper. Increasing the installed capacity of wind turbine with electrical excitation generator leads to design and structural implications, which arise due to the increased size and weight of the generator and thereof the nacelle and tower of the wind turbine.

The indicators of the geological parameter of supply risk show that the currently known iron reserves are almost enough to meet the demand of wind turbines and other background end-use sectors by 2050. It is important to note that although electrical excitation generator needs more iron compared to permanent magnet generator, it does not result in significant difference in iron reserves depletion compared to the permanent magnet generator. This is because wind turbines present only 0.07% of the total projected iron consumption in 2050 considering the Blue MAP scenario. On the other hand, considering the historical trend based projected reserve growth reveals that the amount of iron reserves available by 2050 is nearly 50% more compared to the Reserve2011 estimate. However, considering the Reserve base2009 projection of current iron reserves shows that the amount of iron reserve available in 2050 is 2 times higher compared to the iron Reserve2011.
Furthermore, Figure 4.2 shows the geological supply risk of copper considering the static reserve approach, where the current known reserves of copper seem to already deplete by 2039 for the reference direct-drive wind turbine design in the Blue MAP scenario. However, transition from the reference design case to the electrical excitation generator design alternative would not lead to any faster depletion of reserves as wind turbines represent only 0.4% of total copper consumption in 2050. Nonetheless, considering the historical trend based projection approach for reserve growth, the amount of copper reserves available in 2050 seems to be almost 3 times higher than the currently known reserves. Furthermore, taking the Reserve base2009 projection of current copper reserve into account, the amount of reserve available by 2050 is almost 2 times higher compared to the currently known reserves of copper.

The Conceptual level is the top level in the product design tree (Figure 4.1), where a comparison of reference direct-drive turbine case with the gearbox turbine is presented. Table 2 reveals that the gearbox turbine is 15% less efficient compared to the reference direct-drive wind turbine in terms of electricity output for the same installed capacity. Thus, in order to produce the same electricity output, 1.17 MW of installed capacity is required for a gearbox wind turbine in comparison to a 1 MW direct-drive turbine. Substituting the direct-drive wind turbine offers a clear resource trade-off by avoiding any REEs consumption and significantly reduced copper consumption. However, this substitution leads to considerable design and structural implications.

Though, the gearbox wind turbine consumes only one third of copper compared to the direct-drive turbine (see table 4.1), it does not add any difference to the geological parameter of supply risk in the long run. This is mainly due to the modelled Blue MAP scenario, where it has been assumed that the direct-drive wind turbines will have only 30% market share by 2050, which means that 70% of the newly installed turbines will still be gearbox turbines. This leads to almost similar copper consumption by both wind turbine scenarios up to 2050. Provided the large number of substitutes available across the product design tree, it can be concluded that the dependence of current direct-drive wind technology on rare earths is not very strong, and is thus not detrimental for the large scale implementation of such a technology in future. Finally, implying diversity in design choices of future clean energy systems at individual technology level is opt for reducing dependence on critical resources and thus making it possible to implement clean energy technologies at a wider scale in the long run.
5. Mapping the societal stocks and flows of critical resources

5.1. Material flow analysis

Material flow analysis (MFA) is mapping the physical flows of resources into, through and out of a system defined in space and time. MFA is based on the first law of thermodynamics i.e. the law of conservation of matter which states that matter (mass, energy) can neither be created nor destroyed. This mass and/or energy balancing feature enables MFA to be used as an opt tool for decision-support purposes in the fields of resource, waste and environmental management. MFA makes the sources and sinks of resources visible by balancing their inputs and outputs in a system. This further helps to efficiently manage the resources by identifying the flaws in the system which might go unchecked otherwise (OECD, 2008; Brunner and Rechberger, 2004).

MFA has been widely applied in tracking the societal stocks and flows of mineral resources, especially metals and their alloys at global, regional and national scales (c.f. Chen and Graedel, 2012). MFAs can be static i.e. presenting the snapshot of a system at a specific point in time, and dynamic i.e. showing the stocks and flows in a system over a time interval. Static MFA models usually show the anthropogenic metabolism of resources for a period of one year, thus lack the information about the dynamics in the behaviour of the system under study. Whereas, the comprehensive and consistent set of information provided by dynamic MFAs presents the historical trends in resource consumption, stocks build-up and the resulting waste streams. This further helps in predicting the future behaviour of the system regarding flows and stocks which may lead to proactive measures to tackle any potential environmental problems and resource management issues (Müller et al., 2014). However, as mentioned by Chen and Graedel (2012), majority of the MFAs presenting the metal’s cycles are static due to the inherent complexity and extensive data requirements of dynamic MFA models.

The use of metals has increased at an unprecedented growth rate since the industrial revolution, which has resulted in significant build-up of societal stocks of these metals. This has led to increased focus on the urban mining concept to efficiently collect and recycle these resources at the end of a product’s lifetime (Brunner, 2011). Moreover, during the 20th century, the number of metals in use has grown from a few metals to almost 60 metallic elements today (Zepf et al., 2014; UNEP, 2011). The major industrial/bulk metals such as iron, copper, zinc etc. have a long history of use by humans. Also, these metals are used in large quantities which make their societal stocks concentrated. On the other hand, the use of so called specialty metals such as REEs has increased only during the recent years, where these metals are used in little amounts in a variety of products. This makes their societal stocks highly dispersed leading to challenges
regarding their efficient recovery from their EoL products (Müller et al., 2014). Furthermore, there have been only a few MFAs conducted for these specialty metals compared to e.g. the bulk metals (c.f. Chen and Graedel, 2012). Thus, there is relatively little information available about the detailed flows and stocks of these metals. A number of these speciality metals are considered as critical resources e.g. rare earths, tungsten, indium, antimony, beryllium, germanium, and gallium (European Commission, 2014). Thus, mapping the societal stocks and flows of critical resources at detailed level is of prime importance to evaluate the urban mining potential of these resources, which may alleviate the criticality of these critical resources such as REEs. Following is the case study presenting the comprehensive and dynamic stocks and flows model of NdFeB magnets in Denmark.

5.2. Case study I: MFA of NdFeB magnets for Denmark

In Habib et al. (IV), a dynamic MFA of neodymium and dysprosium contained in NdFeB magnets from 2012 to 2035 is presented for Denmark. The rationale behind doing this study was to estimate the current and future stocks and flows of two key REEs namely neodymium and dysprosium contained in NdFeB magnets by establishing a consistent and comprehensive dataset regarding the weight and composition of these magnets found in a variety of different products. A challenge is that, in general, very little information is available regarding the NdFeB magnets and their composition in different end-use products, and the resulting MFA studies of resource flows in these magnets, therefore, depend on rough estimates and imply large uncertainties. As an example, three recently published studies are based on the estimate/assumption that no dysprosium is used in the Hard Disk Drives (HDDs) contained in computers – an assumption that our more detailed study now shows not to be in line with reality (Sprecher et al., 2014a,b; Rademaker et al., 2013).

5.2.1. Methodological approach

Usually, anthropogenic cycles of metals/elements are comprised of four important material life-cycle stages namely mine production, manufacturing (into products), use and maintenance, and disposal. As the spatial boundary of the current study is confined to Denmark, where neither any mine production nor magnets manufacturing happens, this MFA was divided into four stages: imports, use, waste management and exports. The baseline year for this MFA study is 2012 due to the maximum data availability. However, a dynamic stocks and flows model was established by projecting the study until 2035 in order to enhance our understanding regarding the behavior of system for the defined time period i.e. 2012 -2035, as well as to include proper estimations of the secondary supply potential of neodymium and dysprosium from recycling of NdFeB magnets, as we need to extend the temporal scope beyond the lifetimes of the essential end-use products containing NdFeB magnets to allow the modelling of recovered flows in the MFAs. The outflows to calculate the amount of neodymium and dysprosium appearing in the waste stream have been estimated with the help of average lifetimes of all the different product types (see Table 3.1), where all the products are
supposed to leave the in-use stock at the end of their average lifetime and enter the waste stream. This approach has been used by a number of dynamic MFA studies (Müller et al., 2014).

In-use stocks can be mainly estimated in two different ways, i.e. by a top-down or a bottom-up approach (Müller et al., 2014; Gordon et al., 2006). In this study, the top-down method refers to the estimation of in-use stocks based on the calculation of mass balances of the material flow into use with the help of trade statistics and/or country specific input-output data, and the material flow out of use at the end of product’s lifetime. The bottom-up approach considers estimating the amount of material in the end-use products by detailed waste flow sampling and chemical characterization or using product composition data and combining it with total number of products in the given geographical boundary. In the current study, both approaches are used to estimate the in-use stocks of neodymium and dysprosium contained in NdFeB magnets as they complement each other by filling in the data gaps.

In this study, seven different general product categories were targeted ranging from personal care products to the electricity generators. Within these seven product categories, a total of 18 different product types were dismantled, falling mostly into the product categories of information technology (IT), home appliances and personal care products. Altogether, a total of 157 products were dismantled, their magnets taken out and analyzed. All dismantling of WEEE was done manually using ordinary hand-tools: screw-drivers, hammer, chisel, clamp, universal pliers etc.

The magnets were first demagnetized by thermally treating them in an oven at 400 °C for 45 minutes. After cooling down to room temperature, the nickel (Ni) coating on the magnets was peeled off manually to reveal a fresh surface of the magnet material. The thickness of nickel coating was measured as 50 µm ± 10 µm. A field emission Zeiss XB-1540 scanning electron microscope equipped with an electron dispersive X-ray spectroscopy (EDX) system was then used for elemental identification of the magnet material. Table 5.1 presents the average lifetimes, NdFeB magnet weight and composition for 20 different product types considered in this study.

Due to the inherently uncertain nature of MFA results arising because of data availability and quality concerns along with the diverse nature of data sources, it becomes highly important to address the uncertainty of MFA results in a systematic manner (Laner et al., 2014). In case of rich data availability, uncertainty of the input data for normally distributed variables can be shown with the help of traditional statistics and defined as mean value ± two standard deviations which correspond to approximately 95% confidence interval (x ± y). However, due to the nature of current study where lack of empirical data is the obvious issue, we have performed the data uncertainty analysis based on the method proposed by Hedbrant and Sörme (2001).
### Table 5.1: List of products having NdFeB magnets and their average lifetime*

<table>
<thead>
<tr>
<th>Product category</th>
<th>Products</th>
<th>Average lifetime (years)</th>
<th>Average weight of the magnet (kg/unit)</th>
<th>Magnet composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td>Wind turbines (1 MW)</td>
<td>25</td>
<td>660</td>
<td>Neodymium (Nd) 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dysprosium (Dy) 2</td>
</tr>
<tr>
<td><strong>Medical devices</strong></td>
<td>MRI</td>
<td>10</td>
<td>860</td>
<td>Neodymium (Nd) 29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dysprosium (Dy) 1.63</td>
</tr>
<tr>
<td><strong>Automobiles</strong></td>
<td>Conventional vehicles</td>
<td>16</td>
<td>1.14 until 2011 1.72 from 2012</td>
<td>Neodymium (Nd) 29</td>
</tr>
<tr>
<td></td>
<td>Electric and hybrid vehicles</td>
<td>16</td>
<td>As conventional vehicle + 2 kg of magnet for the motor/generator system</td>
<td>Dysprosium (Dy) 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>As conventional vehicle + 31% Nd for the motor/generator system</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>As conventional vehicle + 6% Dy for the motor/generator system</td>
<td></td>
</tr>
<tr>
<td><strong>Home appliances</strong></td>
<td>Washing machine</td>
<td>11</td>
<td>1.04</td>
<td>Neodymium (Nd) 29</td>
</tr>
<tr>
<td></td>
<td>Dryer</td>
<td>12</td>
<td>0.54</td>
<td>Dysprosium (Dy) 2</td>
</tr>
<tr>
<td></td>
<td>Refrigerator</td>
<td>12</td>
<td>0.49 (freezer) 0.26 (fridge)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air conditioner</td>
<td>10</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vacuum cleaner</td>
<td>7</td>
<td>0.09 (standard) 0.08 (robotic)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Microwave oven</td>
<td>8</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electric toothbrush</td>
<td>2</td>
<td>0.001</td>
<td>Neodymium (Nd) 30</td>
</tr>
<tr>
<td></td>
<td>Body shavers</td>
<td>4</td>
<td>0.001</td>
<td>Dysprosium (Dy) 2</td>
</tr>
<tr>
<td><strong>IT &amp; telecommunication</strong></td>
<td>Desktop computer</td>
<td>10</td>
<td>0.0125</td>
<td>Neodymium (Nd) 30.8</td>
</tr>
<tr>
<td></td>
<td>Laptops</td>
<td>6</td>
<td>0.0034</td>
<td>Dysprosium (Dy) 2.4</td>
</tr>
<tr>
<td></td>
<td>Notebook</td>
<td>4</td>
<td>0.0034</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tablet</td>
<td>3</td>
<td>0.0034</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DVD players</td>
<td>5</td>
<td>0.0014</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Speakers</td>
<td>10</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mobile phones</td>
<td>3</td>
<td>0.0007</td>
<td></td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td>Circulator pumps, industrial applications etc.</td>
<td>20</td>
<td>0.055 (circulator pumps) 25 (circulator pumps)</td>
<td>Neodymium (Nd) 25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dysprosium (Dy) 0.05 (circulator pumps)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*MW: Megawatt; MRI: Magnetic Resonance Imaging; IT: Information Technology; DVD: Digital Video Disc.*

Adapted from Habib et al. (IV)

#### 5.2.2. Key results

As no mining and refining of REEs occurs in Denmark, the flow of NdFeB magnets starts with the import of: first, finished products containing these magnets such as computers and cellphones etc.; second, magnets and/or magnet alloy which is further used in different end-use products e.g. wind turbines and others (named as *miscellaneous category* in this study, containing products e.g., industrial motors, circulator pumps, toys, magnetic bike lights etc.). Results presented in Figures 5.1 & 5.2 reveal that a total of 283 ± 36.5 Mg of neodymium and 17.3 ± 2.1 of dysprosium was imported in 2012 in Denmark in the form of NdFeB magnets, which corresponds to almost 1% of the global neodymium and dysprosium primary production in 2010. The
major import category for NdFeB magnets is wind turbines as Denmark is a leading country in wind turbine technology development and manufacturing.

![Diagram showing material flow analysis of neodymium](image)

Figure 5.1: Summarised results regarding the Material Flow Analysis of neodymium present in NdFeB magnets in Denmark in 2012 (Mg year\(^{-1}\)) (adapted from Habib et al., 2014).

Our estimates show that the in-use stock of neodymium and dysprosium in NdFeB magnets is 1424 ± 375 Mg and 97 ± 12 Mg respectively in 2012. Comparing these numbers to the global in-use stocks of neodymium and dysprosium found in NdFeB magnets (Du and Graedel, 2011b), it becomes evident that the Danish societal stocks represent almost 2.3% of neodymium and 0.6% of dysprosium contained in global NdFeB magnets stocks. This difference between the societal stocks of neodymium and dysprosium is justified by the varying composition of NdFeB magnets in different products, whereas Du and Graedel (2011b) have assumed the same composition of magnets for all the products. Majority of these in-use stocks are contained in wind turbines. In 2012, Denmark exported 53 Mg of neodymium and 1.8 Mg of dysprosium present in NdFeB magnets to the rest of world, mainly in the form of wind turbines and circulator pumps. The overall amount of neodymium and dysprosium present in waste flows in 2012 was nearly 3 Mg and 0.2 Mg respectively, which mainly consisted of IT applications followed by MRI machines. It can be noted that the amount of neodymium and dysprosium present in waste flows is quite low compared to what enters the system. This is mainly because of the increase in use of NdFeB magnets only during the recent years and
long lifetime of key products such as wind turbines (25 years), vehicles (16 years), and home appliances (up to 12 years). However, no neodymium and dysprosium was recovered from these EoL products in 2012 due to the limited data regarding their presence in diverse nature of products as well as non-availability of commercial scale technology to recover these resources in an economically feasible manner. Thus, in the current Danish waste management system, these critical resources end up being impurities in the output material streams of an electronic waste pre-processing facility (see section 5.3).

Figure 5.2: Summarised results regarding the Material Flow Analysis of dysprosium present in NdFeB magnets in Denmark in 2012 (Mg year$^{-1}$) (adapted from Habib et al., IV).

Furthermore, extending our MFA model by 2035 has allowed us to visualize the secondary supply potential of neodymium and dysprosium from major end-use products having long lifetimes such as wind turbines and passenger vehicles. Results presented in Habib et al. (IV) have shown that the overall amount of neodymium and dysprosium found in NdFeB magnets from the resulting waste stream is around 175 Mg and 11.4 Mg in 2035 compared to only 3 Mg and 0.2 Mg respectively in 2012. This estimated high amount of neodymium and dysprosium contained in NdFeB magnets found in Danish waste streams in 2035 is mainly due to the appearance of long lifetime products such as passenger vehicles, home appliances and wind turbines.

Habib et al. (IV) have highlighted that the current maximum theoretical recovery potential of neodymium and dysprosium from NdFeB magnets in Denmark in 2012 is only 3 Mg and 0.2 Mg respectively, which is
equivalent to the amount of neodymium and dysprosium found in three 3 megawatt (MW) direct-drive wind turbines. Thus, it is undoubtedly more attractive and efficient to recover these resources from a major end-user such as one wind turbine compared to hundred thousands of computers and cell phones. As shown in Figures 5.1 & 5.2, almost 60% of the current maximum theoretical recovery potential arises from only one category – IT applications. The major recovery challenge with this category is the diverse nature of end-of-life product types appearing in waste, coupled with the diversity of products even within a single product type. Moreover, the relatively low amounts of neodymium and dysprosium found in IT products render them relatively unattractive for recovery of these resources in an economically efficient manner. Notwithstanding the current small amount of neodymium and dysprosium found in waste streams and the challenges attached to its recovery, the estimated future amount of neodymium and dysprosium contained in NdFeB magnets found in waste stream seems to be higher mainly because of the appearance of major end-use products with long lifetimes such as, passenger vehicles, home appliances and wind turbines. This offers better opportunities for efficient recovery of neodymium and dysprosium from the EoL products in the future.

5.3. Case study II: Tracking the flow of resources in a WEEE treatment facility: case of computer hard disk drives

Habib et al. (V), tracks the flow of resources in a WEEE treatment facility, demonstrated with the help of computer HDDs. The motivation behind this study has been to ascertain the final fate of resources, in particular the critical resources such as rare earths contained in the EoL products, in the existing WEEE handling and treatment system. The main reasons for selecting the computer HDDs as a case study are: a. HDDs are often reported to be the largest end-user of NdFeB magnets (~30%) (Du and Graedel, 2011b); b. almost all the HDDs found in the existing WEEE streams contain the NdFeB magnets; and c. HDDs represent the maximum amount of rare earths present in the existing waste flows (Habib et al., 2014). According to Sprecher et al. (2013b), HDDs offer the most feasible option for the large-scale recovery of neodymium.

5.3.1. Methodological approach

A total of 20 HDDs were analyzed in order to define their material composition. This included 10 from desktop computers (sized 3.5’’) and another 10 from laptops (sized 2.5’’), randomly collected from the local WEEE stream. These HDDs were manually disassembled with the help of hand tools and the individual components were weighed. The elemental composition analysis of the dismantled components was carried out with the help of X-ray fluorescence (XRF) spectroscopy system. The detailed composition of NdFeB magnets was derived from Habib et al. (IV).
MFA was used as an approach to track the flow of resources in the WEEE treatment facility. For this experiment, a total of 244 kg of HDDs, representing 700 2.5'' HDDs and 350 3.5'' HDDs were processed in the WEEE treatment facility. The printed circuit boards (PCBs) were already taken out of the HDDs due to their high economic value, and thus are not represented in the above mentioned total weight of HDDs. The resulting 10 various output fractions were collected in large bags, and transported back to the sorting lab situated at the University of Southern Denmark (SDU). The first two fractions resulting from the filters were not sorted any further because they mainly comprised dust. The remaining eight output fractions were further sorted manually to visualize the material composition of each fraction. As shown in Figure 5.3, five different fractions contained the magnetic dust containing rare earths. This dust was collected and analyzed further to reveal the chemical composition.

After the fine sorting has been completed for the eight different fractions, a mass balance was created for all the components found in HDDs throughout the process flow, representing different material compositions. After performing this initial mass balance, the subsequent processing i.e. the final treatment of these output fractions was also taken into account. The final fate of these fractions was traced until the smelting step in order to estimate the recovery potential of different metals and alloys contained in the HDDs. Based on the expert judgements regarding the material composition of the output fractions, a 2% material processing loss was assumed for the smelting process in order to calculate the maximum recoverable amount of metals and alloys.

5.3.2. Key results

Figure 5.3 elaborates on the overall mass balance of HDDs throughout the treatment plant, as well as the performance of the treatment facility with respect to the separation of various components and materials into the different output fractions. The first thing to be noticed is the difference of nearly 7.3 kg in the output amount compared to the input amount. This is because a big share of this mass did not come out of the shredder and stayed at the bottom of shredder. This missing weight of HDDs in shredder is expected to come out of shredder with the next batch of WEEE processed in the plant. The remaining loss may have happened due to some components being stuck at various points in the plant.
Figure 5.3: Composition of different output fraction resulting from treating the HDDs in a WEEE treatment facility. The pie charts represent the component composition (%) and the bar charts present the material composition of various output fractions (kg). The figure presents the treatment plant layout accompanied with the flow of HDDs throughout the plant. The width of arrows with respect to the output fractions is representative of the share of a particular fraction in the total weight of the output fractions. The dashed arrows represent the subsequent processes for the different output fractions resulting from the WEEE treatment plant (adapted from Habib et al., V).
The largest output fraction was Fraction 8 equivalent to 90.8 kg, resulting from the Eddy-current separator. This fraction mostly consisted of aluminum, which is no surprise as aluminum dominates the total mass of HDDs (see Table 1 in Habib et al., V). The second largest fraction was Fraction 10 originating from the magnetic separator. This fraction weighed almost 56.3 kg and comprised mainly steel followed by aluminum. The major source of steel in this fraction is the top cover of HDDs and the plates used as base for magnets. Fraction 4 was the third biggest output fraction that resulted from the first magnetic separator. The total weight of this fraction was 34.4 kg. As visible from Figure 5.3, this fraction mainly consisted of steel coming from the top and bottom plates for magnets and the top cover of HDDs. Nearly 25% of this fraction consisted of the partially broken HDDs and the residue consisting of spindle motors, screws, spacer rings, broken glass and ceramics from the platters.

In general, it can be seen that none of the output fractions consist of a single material. For example, the purpose of installing the magnetic separators in the WEEE treatment facility is to isolate the ferrous metals from the rest. However, all the four fractions originating from the magnetic separators comprised various materials apart from iron and steel, such as platters. Majority of the platters are made of aluminum coated with thin magnetic layers containing chromium, cobalt, iron, nickel and zinc to enhance the magnetic storage capacity of these platters. Due to these thin layers, the platters are attracted by the magnetic separators and end up in the ferrous stream. The same is the case with voice coil actuators and the spindle motors which were not fully liberated from the adjoining components, and thus appeared in the ferrous fractions.

The ten different output fractions are sent to the final material and/or energy recovery facilities depending on their material composition. These facilities may be located within or outside the country, for example the energy recovery facilities are mostly situated inside Denmark. However, there are no smelters present in Denmark to recover the pure metals or the alloys from the different material fractions resulting from WEEE treatment facilities. Figure 5.3 reveals the fate of different output fractions with the help of dashed arrows and boxes. Figure 5.4 shows the simplified flow of different materials present in HDDs from the WEEE treatment plant to the final treatment of resulting output fractions. From Figures 5.3 & 5.4 it can be visualized that Fractions 1 & 2 are directly sent to the local incinerator because they mainly consist of dust and some mix plastics. The remaining fractions are sent either directly to smelters such as Fractions 3 & 8, or are first sent to the local scrap dealers for fine sorting of different materials and then sent to the smelters sited outside Denmark.

The results presented in Figure 5.4 make it clear that 219 kg of metals and alloys can be recovered from an input stream of 244 kg of HDDs. Out of this, 219 kg of refined metals and alloys, 139.8 kg is Al, 76 kg is steel and 2.8 kg is Cu. This implies that nearly 25 kg are lost throughout the process chain – from EoL HDDs...
to the refined materials. Out of this, nearly 7.3 kg did not appeared in the output fractions of WEEE treatment facility, and the rest is lost during the subsequent processes such as additional shredding and sorting followed by smelting.

**Figure 5.4:** The simplified mass flow of different materials contained in the computer HDDs along with their estimated recovery amounts (adapted from Habib et al., V).

Regarding the flow of rare earths present in the NdFeB magnets contained in the HDDs, Figure 5.3 shows that all the four output fractions originating from the magnetic separators and Fraction 3 do contain considerable amount of the shredded magnets in the form of magnetic dust. This dust sticks to the surfaces of shredded ferrous stream. The total amount of collected dust from the four output fractions was only 2.7 kg. Comparing this amount to the average weight of NdFeB magnets in the input HDDs i.e. equivalent to 6.5 kg, highlights that almost two third of the input magnet fraction was lost during the processing of HDDs. This missing amount of dust containing rare earths has high potential to stick to the internal walls of different processing equipment (e.g. chain shredder, pipes, sides of the conveyer belts and the collection containers) as they are mainly made of ferrous metals. A detailed elemental analysis of the rare earths containing dust collected from five different fractions is shown in Habib et al. (V). The results impart that the amount of rare earths present in this dust fraction was negligible, where neodymium and dysprosium made only 0.9% and 0.1% of the total dust weigh respectively. This translates into 0.02 kg of neodymium and 0.003 kg of dysprosium in the dust fraction. The estimated amount of neodymium and dysprosium in the NdFeB magnets contained in the input stream of HDDs was equivalent to 1.98 kg of neodymium and 0.13 kg of dysprosium.
Comparing this to the amount of neodymium and dysprosium in the output dust fractions reveals that almost 99% of the input rare earths are lost while processing of HDDs in the WEEE treatment facility.

The current WEEE treatment system is focused on material-centric recycling that aims at recycling of bulk materials (metals and alloys) such as aluminum, copper, iron and steel, and the precious metals such as gold, silver and platinum group metals. The critical resources such as rare earths are not on the priority list of materials recycling, due to both, their current volatile market price, and small and dispersed amounts in existing waste flows. The complexity of modern products in terms of material composition and design features cannot be addressed by the existing manner of WEEE recycling. This holds more true during the initial processing of WEEE, where different types of products are shredded together to generate material streams that follows the material-centric recycling chain. The product-centric approach is seen as a potential solution to maximize the material recovery from WEEE in our attempt of closing the material cycle. The increasing focus on design for recycling, design for EoL, design for metallurgy, design for sustainability and similar approaches seem to be promising in order to ensure the resource efficiency in future.
6. Discussion and Perspectives

A broader implementation of clean energy technologies in future is a widely motivated scenario for meeting the climate change goals as well as to reduce our dependency on the non-renewable fossil fuels. However, the transition from the current fossil-based society to a future low-carbon society is fraught with the risk of shifting the supply security problem from one type of non-renewable resources (fossil fuels) to another type (metals). Metals are special in the sense that they are not lost through their consumption like the fossil fuels, but can be recycled from waste. Yet, this large-scale deployment of clean energy technologies in future might be constrained by the decreasing availability of metals. Within this dissertation, an in-depth analysis of potential resource constraints for the emerging clean energy technologies in future is presented through an elaborated case study, along with an insight into the resource criticality assessment methodologies and detailed material flow analysis of critical resources. The key concerns related to this work and the topics of interest for further investigation are enlisted as following sections.

6.1. Long-term availability of metals and the related concerns

The crucial role of metals in shaping the complex societies throughout human history is undisputed. The advent of modern technology, which we are dependent on today, would not have been possible without metals. Therefore, availability of metals has always been a concern for mankind. The limited access to metals has been one of the key motivations behind innovation and substitution. For example, the restricted availability of tin during the Bronze Age is widely seen as the reason for dawn of the Iron Age. During the recent history, the supply disruptions of cobalt in 1970s led to the development of still widely used magnets today – the ferrite magnets (Chapter 2).

The nature of availability concern related to metals has changed over time. During early human history, access to the native metals has been a prime concern because the skills to separate metals from their ores were yet unknown to mankind. This concern had vanished with the advancement of knowledge and technology that increased the access to metals found in a variety of ores and remote locations, which later led to the exponential growth in the rate of mining to satisfy the ever increasing demand of metals for rapidly growing population as well as the complexity of societal build-up. The unparalleled rate of metals production during the last two centuries has shifted the earlier concern of easy access to metals to long-term availability of metals to meet the future generations demand. In 1972, the highly influential book *The Limits to Growth* had highlighted the issue of potential geological scarcity of resources in the years to come. However, the resource supply disruptions experienced during the recent history (c.f. cobalt, palladium, and rare earths) have been an outcome of geopolitical issues instead of geological depletion of resources. This has added a new dimension to the overall resource availability debate i.e. geopolitical supply constraints.
The supply disruptions of cobalt, palladium and rare earths have lead, in general, to a common set of implications and the resulting response by the relevant stakeholders. The immediate result of such supply disruptions has been skyrocketed prices within a short time. The industry has usually responded to these supply disruptions by decreasing the demand through finding the viable substitutes for the resource under supply shortage. Governments have focused on the protective measures such as stockpiling, diversifying the supply of resources by opening new mines in other countries, and decreasing reliance on the dominant producing countries. The positive side of these disruptions has been the innovations made to tackle the risk of reduced availability, and increased focus on enhancing the recycling of metals from the waste flows (Chapter 2). The geopolitical aspect of resource availability will prevail in future too as the metals are geographically bound to the particular geological formations developed over millions of years. This implies that mining of a metal has to take place in the country, where it is found. In order to be resilient to such geopolitically oriented supply constraints in future, it is important for the stakeholders to enhance their awareness of developments in the metals primary production sector. Habib and Wenzel (II) have elaborated on this issue in detail and have shown the dynamic aspect of geopolitical supply risk for metals (Chapter 3). The traditional resource assessment approaches such as LCA are lacking the geopolitical aspect of resource supply constraints, and as such they do not take into account the main cause behind the three major supply disruptions in recent history. Thus, developing an exhaustive methodological framework for resource assessment is seen as a potential topic for further research.

The geological availability concern must not be overlooked, however. During the recent years, this concern has resurfaced and is more frequently voiced, particularly, in context of widely motivated scenario of large-scale deployment of clean energy technologies in future, which might be constrained by the limited geological availability of metals. The geological reserves of metals, in general, have increased over time despite their rapidly growing production in the past (Chapter 3). This has been made possible, by and large, due to the advancement of technology and discovery of resources. However, keeping in mind the finiteness of planet earth, this trend cannot last forever (Bardi, 2014). According to Richard Schodde (2010), most of the growth in copper resources during the past 70 years can be attributed to lowering the cut-off grades of copper mines. Mudd (2010) has already reported the declining ore grades resulting from massive exploitation of good quality resources during the last two centuries. Declining ore grade is further associated to other environmental burdens such as increased mining waste, along with increased amount of water, chemicals and energy required to produce a unit of pure metal. The present resource availability debate, in particular the resource criticality assessment, is lacking a holistic approach to incorporate the decreasing ore grade and the resulting environmental implications as part of the supply risk assessment. Further research is required to assess potential resource constraints regarding both the quantity and quality related aspects of resource availability for the broader implementation of clean energy technologies in future. Moreover, in the context of growing urban stocks of metals, future work must also look into developing the criteria for
including the anthropogenic resources of metals in the overall resource classification system, as metals can be recycled from the EoL products through a well-functioning waste treatment system.

### 6.2. Resource criticality assessment

In general, criticality assessment is similar to the traditionally used risk assessment approach (Glöser et al., 2015; Roelich et al., 2014; Bradshaw et al., 2013). Risk assessment is a parameter to assess the likelihood of a hazard to occur and the resulting damage from its exposure. As an analogy to this, criticality assessment is a tool to assess the supply risk of a resource and the importance of such supply risk for a system under study. The present studies (Graedel et al., 2015; Nassar et al., 2015a; Dawson et al., 2014; European Commission, 2014, 2010; Harper et al., 2015; Nuss et al., 2014; Graedel et al., 2012; Nassar et al., 2012) have incorporated a number of indicators to assess both the supply risk and its importance (see Chapter 3). All of these indicators are dynamic in nature that has been elaborated with the help of geological and geopolitical supply risk indicators in Habib and Wenzel (I and (II). This means that they change over time in result of changing framework conditions. However, most of the existing criticality assessment methodologies have offered a “snapshot” of resource criticality for one specific point in time. The problem of static criticality assessment studies is that they may misguide the policy making institutes by overestimating the problem. This may lead to an artificial short-term resource crisis if protective measures such as stockpiling are taken. Updating the resource criticality assessment studies from time to time is therefore highly recommended. This would act as a monitoring tool too in order to check the progress of initiatives taken to reduce criticality of resources, as well as to guide regarding which measures to take in future in the light of past experiences (Chapter 3).

Furthermore, resource criticality assessment entails expertise from a wide array of fields such as geology, metallurgy, economics, sociology, environmental sciences, product designing and manufacturing. However, the majority of the existing criticality assessment studies have been carried out without involving the in-depth analysis provided by the experts from the relevant fields. In most of the situations, the qualitative scoring based on a mere expert advice and subjective weighting and aggregation of various indicators to achieve the final criticality score are applied, which do not represent real cause-effect relationships.

As discussed in Habib and Wenzel (III), many methods/studies do not include an assessment of resource substitutions and among those which do, almost all have assessed the substitution potential of a resource under investigation by considering a narrow definition of substitution i.e. at an element to element level based on physical and chemical properties of elements (Peck et al., 2015). For example, aluminum has the potential to replace copper in its electrical wiring applications due to high electrical conductivity. Such an approach to assessing vulnerability to the risk of supply disruption of a given resource has validity, but it also overlooks the larger part of technological substitution options and underestimates the capability of
technological development to release technical systems from dependency on specific resources. Another drawback of these judgements is that the substituted material is usually not tested on a commercial scale and thus leads to uncertainty regarding its application in the real world. In Habib and Wenzel (III), a much broader approach to vulnerability assessment is taken – by using a technology specific approach and by looking at options to substitute for a specific resource dependency, not only at the elemental level, but at all levels of product design, from the very overall conceptual design choices to the very detailed component solutions. From the applied direct-drive wind turbine case, it was found that substitutability is very high, and options to release the design of this product concept (direct-drive wind turbine) from dependency on neodymium and dysprosium exist at all levels of design. The rare earth based magnets used in existing generator design can be replaced by a number of commercially available substitutes containing more readily available metals such as iron e.g. the ferrite magnets, though with substantial resource and efficiency trade-offs. In order to provide the similar functional output by substituting the NdFeB magnet with the ferrite magnet, the weight of ferrite magnet is subject to significant increase at the cost of additional iron use (Chapter 4). This is a clear indication of ‘‘rebound effect’’, which is not highlighted in the existing resource criticality assessment studies, and is thus an interesting topic for future work.

This technology specific approach has been judged realistic for further investigation of the key research question of this study, i.e. the question of whether resource criticality can be a constraint for the future development and full scale implementation of clean energy technologies. In the most advanced future renewable energy scenarios applied in this work, it was found that out of the technologies and sectors demanding the rare earths of neodymium and dysprosium, only few constituted the majority of the demand. For further research, it is realistic to do technology specific assessments of those key technologies, and thereby get a good impression of whether they are very vulnerable to supply disruptions of key resources, or whether technological substitutions can be found just as easily as they were here found for the direct-drive wind turbine technology.

Geology plays the central role in criticality assessment of resources. The indicators to assess the supply risk are by and large dependent on the geological knowledge of resources regarding their quantity, quality, location, and production (Graedel and Nassar, 2013). A comprehensive set of geological data for different resources is, thus, the backbone of resource criticality assessment. Our knowledge yet is limited regarding occurrence and concentration of resources in the Earth’s crust (Graedel et al., 2014). Thus far, the US Geological Survey (USGS) has been able to provide the most comprehensive dataset regarding the quantity (differentiated amongst reserves and resources) and location of different resources. It becomes worthwhile to mention that this data is obtained directly from the mining companies and countries, which often have different estimation methods (Speirs et al., 2015). The mining companies have economic benefit in extending and reporting the geological reserves instead of overall Geological Resources, as the reserves can be
exploited economically with the existing technologies (Wellmer, 2008). For this reason, it can be seen that the amount of reserves is updated regularly as opposed to Geological Resources. In some cases, the data related to reserves is also not updated on regular basis as e.g. for strontium. Another piece of valuable information, i.e. the data regarding the reserve base, is not any more provided by the USGS. All these factors are widening the knowledge gaps with respect to geology, and thus increasing the uncertainties in resource criticality assessment. This is, once again (after the publication of The Limits to Growth in 1972), inducing the polarization of global community regarding concerns for resource depletion.

Furthermore, the by-product concern is another geology related issue. Some metals are produced as a by-product of the main metal e.g. gallium, which is mainly produced as a by-product of aluminum. Usually, the so-called specialty metals that are rarer in earth’s crust compared to the abundant metals are produced as by-products. A few of the by-product metals can be produced from their own ores e.g. the rare earths produced in China are mainly produced as a by-product of iron, whereas rare earths produced in Australia and USA are mined as the main product (Elshkaki and Graedel, 2014; Graedel et al., 2014). The metals produced as a by-product are more prone to supply risk as their low concentration in ores is a main hindrance in increasing their production to meet the sudden and high increase in demand, unless they make a good economic case (Nassar et al., 2015b; Afflerbach et al., 2014; Fizaine, 2013). For many of the by-product metals, the reliable estimates of their recoverable resources are limited (Mudd et al., 2013; Crowson, 2011). The sparse data related to geological reserves of the by-product metals is another challenge for resource criticality assessment to be tackled carefully in future, and an elaboration of the business case of such by-product mining operation to react to an increasing demand for the by-product is a relevant research topic of the future: at which price-level of these by-products will they provide a high enough profit margin to allow for increased mining in these types of mining operations?

6.3. Role of recycling in lowering the geopolitical supply risk

The role of recycling has been discussed in recent studies in order to decrease the burden on primary supply to meet the future high demand (Elshkaki and Graedel, 2013; Hoenderdaal et al., 2013; Habib and Wenzel, I) as well as to lower the geopolitical supply risk of the so called critical resources such as rare earths (Rademaker et al., 2013; Habib and Wenzel, I). The majority of these studies have shown the secondary supply potential originating from recycling of EoL products at a global scale. The drawback of such analyses is that the global scale estimation of secondary supply is less useful in quantifying the impact of increased secondary supply on geopolitical supply risk (estimated with the help of HHI). For this reason, estimating the future demand, and mapping the flows and stocks of resource at a country or regional level becomes imperative to estimate the future secondary supply potential within these spatial boundaries. This can help in estimating the effect of recycling on the geopolitical supply risk in a robust manner. Yet, there may emerge other challenges questioning such an endeavor. For example, it is not necessarily so that the country with
substantial recovery potential of critical resources from waste flows has the economically viable technological means to accomplish the efficient recycling systems. In that case, the EoL products might be shipped to other countries having the economically feasible technological solutions. A detailed evaluation of these concerns is open for further research.

6.4. Recovery of critical resources from waste flows

Recovery of critical resources from waste flows is increasingly seen as a prioritised solution to decrease the criticality of resources by lowering their supply risk. Rare earths are a good example here due to their high supply risk and increasing demand in the modern technologies (Habib and Wenzel, I; Habib et al., IV). The current EoL recycling rate of rare earths is negligible (Reck and Graedel, 2012; UNEP, 2011; Graedel et al., 2011). Habib et al. (IV) have shown in detail the stocks and flows of rare earths contained in the NdFeB magnets, where it becomes clear that the economically efficient recovery of these elements from waste is challenged due to their wide distribution and low amount present in the existing waste flows. Notwithstanding their current small recovery potential, however, the amount of rare earths is estimated to increase in the future waste flows due to the key end-use products with long lifetimes such as wind turbines and passenger vehicles appearing in the future waste. This implies that developing the commercial scale recovery technologies for rare earths from a broad range of end-use products is crucial to increase their EoL recycling rate in future (Chapter 5).

Habib et al. (V) have highlighted the complete loss of rare earths in the existing WEEE treatment system. Therefore, it is suggested to disassemble the magnets containing rare earths before treating the products in the conventional shredding based WEEE treatment facilities. Yet, collection of end-use products containing these magnets, their dismantling to isolate magnets followed by further processing remains a technological and logistic challenge. A detailed investigation of stocks and flows of critical resources is worthwhile to estimate their recovery potential in the current and future waste flows, in order to enhance their recovery in future. Additionally, labelling of products containing the critical resources for their separate handling in the WEEE treatment facilities, harmonized design of similar products by different producers to optimize their sorting and dismantling manually or using robotic solutions, and updating the existing WEEE treatment technologies according to the new needs (c.f. UNEP, 2013) are a subject of further research.
7. Conclusion

The main findings of this PhD work can be summarized as follows:

1) The transition from the current fossil-based society to a future low-carbon society entails dependency on metals in general, and the specialty metals such as rare earths in particular. Based on knowledge of today’s technological dependency on neodymium and dysprosium, their estimated future demand ranges from 146 to 305 Gg year\(^{-1}\) and 14 to 35 Gg year\(^{-1}\) respectively by 2050. This is 4 – 9 times higher for neodymium and 5 – 12 times higher for dysprosium in comparison to their primary production in 2010. A transition to a low-carbon society, thus, implies that either a highly accelerated rate of mining is required to satisfy the estimated high demand of neodymium and dysprosium in the scenarios or a radical change in technologies compared to today’s state-of-the-art is required to avoid the technological dependency on neodymium and dysprosium by substituting them with other solutions.

2) The amount of currently known geological reserves (in 2011) of neodymium and dysprosium remaining after considering their cumulative demand in the ultimate renewable energy scenario and the business-as-usual scenario by 2050 is equivalent to 63 – 75% and 56 – 75% respectively. Taking the ultimate renewable energy scenario into account by considering the resource dependency of presently known technologies and a rather stable rate of demand growth from 2050 to 2100, the presently known and economically exploitable reserves of neodymium and dysprosium seem to last until 2070 and 2065 respectively. Nevertheless, the geological reserves are only a small part of the overall Geological Resources, and further, the reserve estimates are dynamic entities and they are subject to grow over time as a result of new discoveries, technology development and economic feasibility. For this reason, neodymium and dysprosium reserves are not judged to be depleted in several hundred years.

3) Recycling is not likely to play a major role in reducing the burden on primary supply to meet the estimated high demand in the short-to-medium term. The long lifetime of key end-uses such as wind turbines and passenger vehicles, and the non-availability of commercial scale recycling technologies are main obstacles here. However, recycling seems to lessen the demand of primary production resulting in delaying the reserve depletion, as well as playing a significant role in reducing the geopolitical supply risk on the long term.

4) Resource criticality is a dynamic aspect, which is subject to change overtime. This is because of all the underlying parameters used to assess criticality that are themselves dynamic in nature. Most of the existing criticality assessment studies present only a ”snapshot” in time neglecting the ongoing developments, which is misleading the decision making bodies regarding the establishment of renewable energy infrastructure in future. This has been demonstrated with the help of geological and geopolitical risk assessment of the resources required for the broad deployment of current state-of-the-art wind turbine technology by 2050. The results have clearly shown that neither geological nor
CONCLUSION

geopolitical issues seem to be a hindrance in a wide scale implementation of the clean energy technologies in the longer term.

5) The suggested methodological framework to assess resource criticality in a technology specific perspective has offered a systematic manner to evaluate various design alternatives at different levels of a product technology design tree. Evaluating the current state-of-the-art wind turbine technology against different design substitutes has clearly demonstrated that the technological concept in question is not dependent on the rare earths for its broader application in the future, as the rare earths based solutions can be easily substituted with a number of available alternatives independent of rare earths. Yet, this substitution might entail substantial resource and performance trade-offs which in turn must be assessed.

6) The detailed material flow analysis (MFA) of neodymium-iron-boron (NdFeB) magnets in Denmark has shown that 975 Mg of magnets were imported in Denmark in 2012. This amount corresponded to 283 Mg of neodymium and 17 Mg of dysprosium, which was equivalent to 1% of global mine production of these elements in 2010. The estimated amount of neodymium and dysprosium contained in NdFeB magnets found in the waste stream was equivalent to 3 and 0.2 Mg respectively. The recovery potential of rare earths from the present waste stream is, thus, significantly low, which is mainly because of the long lifetimes of key end-uses delaying their appearance in the waste. The existing waste flows are dominated by the IT & telecommunication applications, in particular the EoL mobile phones and hard disk drives found in EoL computers. The small amount of rare earths per unit of these products poses challenges for their economically feasible recovery. Nonetheless, the amount of rare earths contained in the NdFeB magnets found in waste is estimated to rise significantly by 2035, which is equivalent to 175 Mg year\(^{-1}\) of neodymium and 11 Mg year\(^{-1}\) of dysprosium. Thus, establishing the commercial scale recycling technologies for the rare earths contained in NdFeB magnets would be required for the efficient and economically feasible recovery of these resources from waste in future.

7) Tracking the flow of neodymium and dysprosium contained in the NdFeB magnets of computer hard disk drives in a conventional WEEE treatment facility has revealed the complete loss of rare earths while processing. This is primarily due to the brittle nature of magnets, converting them into powder upon shredding. The powder retains its magnetism and sticks to the ferrous surfaces of the equipment in the WEEE treatment plant as well as the ferrous fractions coming out of the treatment plant. This clearly shows that the magnets should be disassembled from their products before sending the products to shredder. However, separating magnets from their end-use products, their handling, and final processing remains a technological and logistic challenge for the existing system.
8. References


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