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UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

International Centre for Environmental Science

Mining Anthropogenic and Geological Deposits: Evaluating the Accessibility of Scarce Metals from End of Life Products and the Earth's Crust under Sustainability Considerations

by

Sandra Regina Mueller

Thesis for the degree of Doctor of Philosophy

October 2018

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ABSTRACT

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This thesis includes three main chapters with the aim to develop a methodological framework for characterising and evaluating the accessibility of End of Life (EoL) products and the Earth's Crust. Chapter 4 presents a novel characterisation and evaluation of End of Life products by means of 'geological' approaches that are based on mining deposits of the geosphere (MDG). For method development of the characterisation and evaluation, four expert workshops were implemented. The results showed an innovative and systematic characterisation of the 'geological setting' of a deposit. Further, the results demonstrated a pioneering evaluation of the knowledge and certainty (geological knowledge) by means of the UNFC classification. The characterisation and evaluation was applied on three case studies of mining deposits of the anthroposphere (MDA), which provides a basis for Chapter 5 and highlighted the need for further research.

Chapter 5 presents the methodological framework that investigates the characterisation and evaluation of both MDA and MDG by investigating the prerequisite for recovery: accessibility. The accessibility evaluation was developed by means of a quantitative linguistic concept extraction. This framework was elucidated and then applied to analyse three anthropogenic and one geological deposits. The results of the linguistic investigation showed that accessibility is at the semantic intersection of 'availability' and 'approachability'. The later terminology and its concept were not yet used, which poses a novel aspect of this study. The results of applying the accessibility evaluation demonstrated that an active mining operation and subsequent processing of rare earth elements showed 'moderate' approachability regarding 'society' and 'environment' and 'high' availability. Conversely, three REE case studies from MDA demonstrated as not being accessible in early project development.

In Chapter 6, the accessibility evaluation was refined and confirmed by means of a Delphi survey that involved 48 experts. This resulted in a consolidated framework that was based on 12 applied (semi-) quantitative indicators. These results of four case studies showed 'lower' accessibility for knowledge and certainty (geological knowledge) of MDA. Further, the results of 'economy', 'society' and 'envi-

ronment' indicated a clear discrepancy between developed and developing countries. This novel information enables policy makers to make informed decisions that could highlight the potential for in-depth investigations to secure material supply in the long-term. However, the results also emphasised there is little high quality underlying data along the supply chain and within waste management.

Overall, this thesis presents a novel, innovative and practical methodological framework that can provide valuable knowledge to support decision makers at the government level in characterising and evaluating the accessibility of both EoL products and the Earth's crust under sustainability considerations.

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DECLARATION OF AUTHORSHIP

I, Sandra Regina Mueller declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Mining Anthropogenic and Geological Deposits: Evaluating the Accessibility of Scarce Metals from End of Life Products and the Earth's Crust under Sustainability Considerations

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;

2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

3. Where I have consulted the published work of others, this is always clearly attributed;

4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

5. I have acknowledged all main sources of help;

6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

7. Parts of this work have been published as:

Mueller, S.R., Wäger, P.A., Widmer, R. and Williams, I.D., 2015. A geological reconnaissance of electrical and electronic waste as a source for rare earth metals. Waste Management 45: 226–234.

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Signed: ……

Date: ……

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Motivation – A poem to the noble circular raw material flow

Round, rounder, the roundest

Led by round harmony from one cycle into the next.

We, raw materials, are the origin of tool construction, the products and the electrolytes in our blood.

Each individual electrolyte is essential.
Without electrolytes exists no prospecting life.
Without tools exists no products.
Without products exists no medical support for repairing the blood with electrolytes.
The tools are therefore in harmony with the requirements in the blood.

Each raw material is chosen and tested with diligence.
Each tested product is deployed with reliability.
Each reliable deployment requires small amounts of raw material.

Where do these small amounts of raw materials go?
Importantly, where do the retired reliable products go?
Chosen with diligence, where do the raw materials in the products go?

They are collected, separated, sterilised, and mixed with other products.
These products, with diligently chosen raw materials, will then be crushed and melted into their pure elemental harmonic shape.

What goes around comes around.

This is the round story of the circular raw material flow.

Actually, how is the story of the circular effort of one cycle?
Disproportionately distributed… …over the entire lifecycle.

In short:
Diligently chosen –
Reliable in deployment –
Retired –
Separated –
Mixed –
Crushed –
Melted –
Diligently chosen –
Oh dear, disproportionally rounded.

With much love but disproportional effort in the circular material flow. This causes currently a disharmony in the circular raw material flow.
Oh dear, separating and then later mixing.

This is the round story of the circular effort of one material cycle.

Round, rounder, the roundest

With love to the noble circular raw material flow.

Glossary of key terms

Table 1: Glossary of key terms, which are structured according to the topics: natural cycle, product management, geological material production, geological material production, materials and its cyclic flow from primary material to secondary (anthropogenic) material, accessibility, and method.

Sub-topic	Term	Definition	Reference
Natural Cycle			
Rocks	Earth's crust	The outer layer of the Earth. In this study, this term is used interchangeably with geosphere.	(Vocabulary.com Dictionary, 2018)
	Geosphere	Any of the almost spherical concentric regions of the earth and its atmosphere, especially the lithosphere. In this study, this term is used interchangeably with Earth's crust.	(Oxford Dictionaries, 2018b)
	Lithosphere	The upper layer of the Earth's crust, which is 1200 km thick.	(Gupta, 2003a)
	Sedimentary rock	A layered rock formed as a result of compaction and / o r consolidation of sediments, including a clastic rock such as sandstone or siltstone, a chemical rock such as rock salt or gypsum.	(Buryakovsky, *et al.,* 2012)
	Metamorphic rock	A rock derived from re-existing rocks by mineralogical, chemical, and structural alterations caused by processes within the Earth's crust at high temperatures and pressures.	(Buryakovsky *et al.*, 2012)
	Magmatic rock	A rock mass formed by the solidification of material poured (when molten) into the Earth's crust or onto its surface.	(Buryakovsky *et al.*, 2012)
Process	Alteration	Alteration is a mineralogical change at low pressures due to invading fluids or the influence of oxygen.	(Alden, 2012)
	Erosion	The physical and/or chemical processes whereby the earthy and rocky materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously removed from one place to another by running water (including rainfall), waves and currents, moving ice, or wind.	(Buryakovsky, *et al.*, 2012)
	Subduction	A key process in plate tectonics that involves the movement of an oceanic plate and some of its associated sediments underneath a continental plate or another oceanic plate.	(Henke, 2009)
	Subsidence	Local or regional down warping of a land surface due to tectonic or sediment loading. Subsidence of land sur-	(Buryakovsky, *et al.*, 2012)

Sub-topic	Term	Definition	Reference
		face can occur as a result of fluid (oil and /or water) withdrawal from the oil/gas- and water-producing formations.	
	Melt migration	Example in context: - Partial melting and melt mitigation are the principle mechanisms for transfer of solids and gaseous material to the Earth's surface and atmosphere (Sammonds and Thompson, 2007). - In addition to pressure and temperature of the potential melting reactions, melt mitigation can occur at a variety of different melt fractions, depending on tectonic environment (e.g. whether or not deformation is present) (Dosseto *et al.,* 2010).	(Sammonds and Thompson, 2007; Dosseto, Turner and Van-Orman, 2010)
State	Exposure	Example in context: Brick, mud: Brick dried by exposure to the atmosphere and the heat of the sun.	(Goffer, 2007)
Transformation	Weathering	The destructive physical and /or chemical processes constituting that part of erosion whereby earthy and rocky material on exposure to atmospheric agents at or near the Earth's surface are changed in character (colour, texture, composition, firmness, or form), with little or no transport of the loosened or altered material.	(Buryakovsky, *et al.,* 2012)
	Sedimentation	The accumulation of sediment in a natural environment, including: rivers, lakes, seas, oceans, and deserts.	(Henke, 2009; Buryakovsky *et al.*, 2012)
	Lithification	Process of converting unconsolidated sediments to rocks by the addition of mineral cement or by compaction.	(Henke, 2009; Buryakovsky *et al.*, 2012)
	Concentrating	Example in context: - Chert is a form of silica, which often concentrates in layers - Benefication is the processing of rocks and minerals to reduce impurities. In ore processing, the up-graded fraction is called a concentrate and the waste a gangue.	(Oates, 1998)
	Metamorphism	Sedimentary, igneous, or previously metamorphosed rocks that have been considerably altered by subsurface heat (usually above 200 ◦C), pressure, and/or grinding, but not to the point of melting.	(Henke, 2009)

Sub-topic	Term	Definition	Reference
	Diagenesis	Any physical, chemical or biological change undergone by a sediment after initial deposition and rock formation, excluding surface alteration (weathering) and metamorphism. Such changes happen at relatively low temperatures and pressures and result in transformations to the rock's original mineralogy and texture.	(Árkai, Sassi and Desmons, 2003)
	Melting	The physical process of a solid becoming a liquid.	(Goffer, 2007)
	Crystallization	The formation of crystals from a melt, solution, or gas.	(Goffer, 2007)
	Recrystallization	The process of forming new crystals without a change in chemical composition.	(Retallack, 2008)
Geological material production			
Mining	Mining (Cycle)	The modern mining industry moves from exploration and deposit discovery to evaluation through development to operation and finally followed by rehabilitation. This is often known as the ‘mining cycle’. It is this continually evolving cycle of the deposits discovered and developed versus the known prospects/resources remaining which is a key issue surrounding resource depletion/availability.	(Mudd, 2007)
Mining project	Prospect	A restricted volume of ground that is considered to have the possibility of directly hosting an ore body and is usually a named geographical location. The prospect could be outcropping mineralization, an old mine, an area selected on the basis of some geological idea, or perhaps some anomalous feature of the environment (usually a geophysical or geochemical measurement) that can be interpreted as having a close spatial link with ore. Prospects are the basic units with which explorers work. The explorer’s job is to generate new prospects and then to search them in order to locate and define any ore body that might lie within them.	(Marjoribanks, 2010)
	Exploration	A process in the search for mineral deposits. This process consists of the general patterns: reconnaissance exploration, detailed exploration and evaluation.	(Pohl, 2011)

Sub-topic	Term	Definition	Reference
	Reconnaissance Exploration	The first step of the exploration process. The exploration process consists of the general patterns: reconnaissance exploration, detailed exploration and evaluation.	(Pohl, 2011)
	Detailed Exploration	The second step of the exploration process. The exploration process consists of the general patterns: reconnaissance exploration, detailed exploration and evaluation.	(Pohl, 2011)
	Evaluation	The third and final step of the exploration process. The exploration process consists of the general patterns: reconnaissance exploration, detailed exploration and evaluation.	(Pohl, 2011)
	Deposit	A deposit is any accumulation of a mineral or a group of minerals that may be economically valuable.	(European Commission, 2010)
	Reserve	A reserve is the part of the resource which has been fully geologically evaluated and is commercially and legally mineable.	(European Commission, 2010)
	Reserve base	The reserve base is the reserve of a resource plus those parts of the resource that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics	(European Commission, 2010)
	Resource	A resource is a natural concentration of minerals or a body of rock that is, or may become, of potential economic interest as a basis for the extraction of a mineral commodity.	(European Commission, 2010)
	Mineral Resource	Mineral resources are inferred, indicated or measured resources, reflecting an increasing level of geological knowledge and confidence. This includes recoverable (geologically, technically) and currently economic (above cut-off grade and favourable mineralogy) quantities of ore deposits.	(United Nations, 2013)
	Ore	Accumulations of metals and minerals at a particular location.	(McLaughlin, 1956)
	Static lifetime	The static lifetime is the ratio between	(European

Sub-topic	Term	Definition	Reference
		reserve or reserve base and annual mine production.	Commission, 2010)
Processing	Processing	Example in context: Batch processing: the fabrication of materials or objects in batches.	(Goffer, 2007)
	Mineral Processing (ore processing, ore dressing)	Follows mining (Wills *et al.*, 2006) and reduces waste (gangue) and enrich ore minerals to 'concentrates' of metals (e.g. copper concentrate with 62 wt. % Cu) on mine-site (Pohl, 2011) and produces a commercial end product of products such as iron ore and coal (Wills *et al.*, 2006), which can be sold to smelters (Pohl, 2011). Further, it produces tailings that can be disposed of in an environmentally safe manner (Petruk, 2000).	(Petruk, 2000; Wills *et al.*, 2006; Pohl, 2011)
	Smelting	The basic process by which metals are produced from metalliferous ores; it is usually a pyrometallurgical process that involves the chemical reduction and recovery of the metals contained in the ores.	(Kesler, 1994; Goffer, 2007)
	Refining	The removal of impurities from a substance.	(Goffer, 2007)
Product management			
Product cycle	Manufacturing	Manufacturing processes can be divided into two basic types: (1) processing operations and (2) assembly operations. A processing operation transforms a work material from one state of completion to a more advanced state that is closer to the final desired product. It adds value by changing the geometry, properties, or appearance of the starting material In general, processing operations are performed on discrete work parts, but some processing operations are also applicable to assembled items. An assembly operation joins two or more components in order to create a new entity, called an assembly, subassembly; or some other term that refers to the joining process. (Groover, 2007). The transformation of materials and information into goods for the satisfaction of human needs (Chryssolouris and Hardt, 2003). Manufacturing pro-	(Chryssolouris and Hardt, 2003; Chryssolouris., 2006; Groover, 2007)

Sub-topic	Term	Definition	Reference
		cesses can be further divided into discrete parts processes and continuous processes. The metal working industry, where many single items are produced, uses discrete parts manufacturing. Chemical processing, used, for example, in the film- or fibermaking industries, uses continuous processing (Chryssolouris., 2006).	
	Use	The time from starting use of the products, which have a specific function, e.g. printer, i.e. delivery to the customer until such a products no longer can fulfil the desired customer's needs.	(Lindahl *et al.,* 2006)
	Waste management	The collection, transport, recovery and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker.	(EU, 2008)
	Collection	"Gathering of WEEE, including the preliminary sorting and preliminary storage of WEEE for the purpose of transportation to a logistics facility or a treatment facility."	(Cenelec, 2014)
	Manual and mechanical processing	Process to separate and concentrate metals from waste materials into different waste and end-of-waste fractions for further metallurgical processing	(ISO, 2017)
	Metallurgical extraction	The process, of extracting something concerned with the properties of metals and their production and purification, especially using effort or force.	(Oxford Dictionaries, 2017c, 2017a)
	Refining	see geological material production	
Materials and its cyclic flow from primary material to secondary (anthropogenic) material			
	Alloy	Alloys consist of different elements and are in a microscopic scale inhomogeneous, due to the precipitation of some phases during solidifications. The object of alloying is to make materials that are more ductile, harder or resistant to corrosion, or that have more attractive appearance (such as colour or lustre).	(Rankin, 2011)
	Basic material	Materials that undergo some processing to be in a form suitable for processing, examples are steel sheet or cooper wire.	(Rankin, 2011)

Sub-topic	Term	Definition	Reference
	By-product metal	Recovered metals, which occur interstitially in the ores of metals with similar physical and chemical properties.	(Graedel *et al.*, 2012)
	Engineering material	Materials that involves processing, which leads to predominantly physical change in its use.	(Rankin, 2011)
	Mineral	Minerals are individual components within rocks that are generally defined according to their chemical composition and crystal structure.	(Nickel, 2005)
	Primary raw materials	Materials are materials extracted from the geosphere	(Gunn, 2014)
	Raw material	Materials in their natural, unprocessed or minimally processed state, such as iron ore, wool or tree logs	(Rankin, 2011)
	Scarce metals	Geochemically scarce metals are those metals, whose crustal abundance is <0.01 weight-%.	(Wäger et al., 2012)
	Secondary material	Materials sourced from recycling	(Gunn, 2014)
	Recovery rate	It is used along the supply chain starting from mineral processing, e.g. grinding up to obtaining the raw material (Peiró and Méndez, 2013). Simoni (2012) pointed out that recovery follows after: mining, extraction and then recovery (Simoni, 2012)	(Simoni, 2012; Peiró and Méndez, 2013)
	Mining recovery rate	Percentage of ore recovered during the mining process.	(Bartsch-Winkler, 1989; Watson *et al.*, 2014)
	Mining rate	Ore or gas mining of a certain volume in a given time. Unit can be [t / year].	(Leite and Dimitrakopoulos, 2007)
	Dissipation	The “dilution” of materials into the anthroposphere in such a way that a material recovery is difficult or impossible.	(Wäger et al., 2012; Zimmermann and Gößling-Reisemann, 2013)
	Recovery rate in geology	A term used in e.g. physical separation, such as milling, processing, such as smelt and refine; to indicate the proportion of valuable material obtained in the processing of an ore. It is generally stated as a percentage of the material recovered compared to the total material present.	(University of Texas, 2005, Hilton and O’brien, 2009)
	Recovery rate in waste management	A function of efficiency of the different process steps (physical separation and	(van Schaik and Reuter, 2004)

Sub-topic	Term	Definition	Reference
		metallurgy). Note: this is alike the recovery rate in geology	
	Processing recovery rate	The percentage of mineral that remains after losses during processing	(USGS, 2013) (Hilton and O'brien, 2009)
	Collection rate	A percent rate; understood as a storage activity pending collection in facilities where waste is unloaded in order to permit its preparation for further transport for recovery or disposal elsewhere.	Directive 2008/98/EC on waste (Waste Framework Directive) (EU, 2008)
	Recovery in waste management	Any operation with the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a non-exhaustive list of recovery operations	Directive 2008/98/EC on waste (Waste Framework Directive) (EU, 2008)
	Recycling in waste management	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations;	Directive 2008/98/EC on waste (Waste Framework Directive) (EU, 2008)
Accessibility			
	Accessibility	Raw materials are accessible if there are no 'significant' constraints (e.g. ownership, protected areas, environmental restrictions) to 'get to' the material of interest in order for potential treatment or production	(own definition published in: Mueller *et al.*, 2017)
	Availability	The quality of being at hand when needed.	(own definition published in: Mueller *et al.*, 2017)
	Approachability	The attribute of being easy to meet or deal with	(own definition published in: Mueller *et al.*, 2017)
	Urban	Relating to or concerned with a human build area that that contains a concentrated amount of End-of-Life products and the Earth's crust, which can be a	(adopted from WordNet, 2016d)

Sub-topic	Term	Definition	Reference
		deposit, processing site or manufacturer.	
	Technosphere	The technosphere is defined as material stocks established by human agency, and which as we shall see originates from technological processes, in contrast to stocks in the lithosphere established by slow, primary geological processes.	(Johansson *et al.*, 2012)
	Barrier	Any condition that makes it difficult to make progress or to achieve an objective. For modelling a network, barriers can be included as a non-urban restriction, which can encompass such as political, economic, legal or physical barriers.	(Spiekermann *et al.*, 2011; WordNet, 2016a)
	Constraint	Something that controls what you do by keeping you within particular limits. For modelling a network, constraints can be included by the use of the links (edges) within the urban network: environmental emissions of using the urban network; or by capacity constraints: maximal urban network usage.	(Spiekermann *et al.*, 2011; Cambridge English Dictionary, 2016a)
	Component	A part that combines with other parts to form something bigger.	(Cambridge English Dictionary, 2016)
	Sub-component	A sub part that combines with other parts to form something bigger.	(adopted from Cambridge English Dictionary, 2016a)
	Operational step	The action to control the functioning of a specific process along the supply chain and waste management.	(adopted from Oxford Dictionaries, 2017e)
	Operational section	For each operational step, there is a distinct division part.	(adopted from Oxford Dictionaries, 2017g)
	Geological knowledge	The understanding of the context of the intended material deposit; including: type, grade and mine life.	(own definition published in: Mueller *et al.,* 2015)
	Technology	1) The application of the knowledge and usage of tools (such as machines or utensils) and techniques to control one's environment. (WordNet, 2015), which highlights the ability of innovation in technologies for both mining, processing. (Giurco and Cooper, 2012)	(Giurco and Cooper, 2012, WordNet, 2015)

Sub-topic	Term	Definition	Reference
	Economy	The system of production and distribution and consumption of minerals, including costs, prices of obtaining the material of interest and information on the market stability, i.e. sensitivity or volatility and investments.	(Giurco and Cooper, 2012)
	Society	Networks together with shared norms, values, and understandings that facilitate co-operation within or among groups including working condition and labour costs, human rights and labour situation, and product responsibility.	(UNU, 2012)
	Environment	The natural and resource condition of the environment and ecosystem processes including impacts on nature: ecosystem, water, land, air and living organisms and abiotic resource depletion.	(Giurco and Cooper, 2012);
	Indicator	Statistical measures that are used to consolidate complex data into a simple number or rank that is meaningful to policy makers and the public.	(Merry, 2011)
	Composite indicator	“A composite indicator is formed when individual indicators are compiled into a single index, on the basis of an underlying model of the multi-dimensional concept that is being measured.”	(OECD, 2013)
Method			
	Operationalization	"The transformation of an abstract, theoretical concept into something concrete, observable, and measurable in an empirical research project. Operational definitions are pragmatic and realistic indicators of more diffuse notions."	(Scott and Marshall, 2009)
	Sustainability vision	"We do not inherit the earth from our ancestors; we borrow it from our children".	(Saint-Exupery, 1951)
	Sustainability as used for this research	“Certainly a sustainable society would use non-renewable gifts from the Earth’s crust more thoughtfully and efficiently than the present world does. It would price them properly, thereby keeping more of them ‘accessible’ for future generations. But there is no reason not to use them, so long as their use meets the criteria of sustainability already defined, namely that they do not overwhelm a natural sink and that	(adopted from Meadows, Randers and Meadows (2004)

Sub-topic	Term	Definition	Reference
		renewable substitutes are developed."	
	Method	"A particular procedure for accomplishing or approaching something, especially a systematic or established one."	(Oxford Dictionaries, 2017d)
	Framework	"A basic structure underlying a system, concept, or text."	(Oxford Dictionaries, 2017b)
	Methodological framework	To provide a methodological procedure that results are summarised in a basic structure, i.e. framework.	(adopted from Winterstetter, 2016)
	Evaluation	The making of a judgement about the amount, number, or value of something; assessment.	(Oxford Dictionaries, 2017f)
	Classification	The action or process of categorizing something into classes or groups.	(Oxford Dictionaries, 2017f)
	Classifying	(Of an adjective) describing the class that a head noun belongs to and characterized by not having a comparative or superlative (for example American, mortal). Contrasted with gradable, qualitative	(Oxford Dictionaries, 2017f)
	Assessment	"The act of judging or deciding the amount, value, quality, or importance of something, or the judgment or decision that is made."	(Cambridge English Dictionary, 2018)
	Sustainability assessment	A complex evaluation method in a broad environmental, economic and social context.	(Sala, Ciuffo and Nijkamp, 2015)
	Opportunistic corpora	a selection of texts that are needed for the present purpose. They often represents an incomplete collection of electronic texts.	(Hausser, 2014); (Sekhar, 2008)
	Synsets	A set of synonyms.	(WordNet, 2014)
	WordNe	large lexical database of English that covers a wide range of words, establishes cross linkages between them and is widely applied in linguistics. Nouns, verbs, adjectives and adverbs are grouped into sets of cognitive synonyms (synsets), each expressing a distinct concept.	(WordNet, 2014)
	Semantic	Analysis of the meaning of a word.	(Weinhofer, 2010)

Abbreviations

AHP	Analytical hierarchy process
Ap.	Approachability
AUS	Australia
Av.	Availability
BAFU	Federal Office of the Environment from Switzerland (German abbreviation)
BGS	British geological survey
CH	Switzerland
CHF	Swiss franc
CN	China
Co	Completeness
CO_2 eq.	Carbon dioxide equivalent
DQR	Data quality ranking
EC	Linguistic corpus regarding existing conceptualisations
EEE	Electrical and electronic equipment
EoL	End-of-life
EPI	Environmental performance index
Er	Erbium
EU	European Union
Eu	Europium
Eu_2O_3	Europium oxide
EUR	Euro
FOEN	Federal Office of the Environment from Switzerland (English abbreviation)
GC	Geographical correlation
GDP	Gross domestic product
GWP	Global Warming Potential
HDD	Hard drive disks
HHI	Herfindahl-Hirschman Index
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
MA	Linguistic corpus regarding mining the anthroposphere
MatCH	Material flows Switzerland
MDA	Mining deposits in the anthroposphere
MDG	Mining deposits in the geosphere

MFA	Material flow assessment
MG	Linguistic corpus regarding mining the geosphere
MRoPI$_r$	Multi-dimensional methodology supporting a safeguarding decision on the future access to mineral resources
N/A	Not available
Nd	Neodymium
$Nd_2Fe_{14}B$	Neodymium–iron–boron
Nd_2O_3	Neodymium-oxide
NRC	National research council of the United States
OECD	Organisation for Economic Co-operation and Development
ORDEE	Ordinance for the return, take-back, and disposal of electrical and electronic equipment
PCB	Printed circuit boards
PPI	Policy Potential Index
ProSUM	Prospecting secondary raw materials in the urban mine and mining wastes
QDA	Qualitative data assessment
R	Reliability
ReCiPe	RIVM and Radboud University, CML, and PRé Consultants
REE	Rare earth elements
REO	Rare earth oxide
SDA	Societal and acceptance dimension
SSD	Solid state disks
TeC	Temporal correlation
TMR	Total Material Requirement
UBP	Environmental impact points
UK	United Kingdom
UNEP	United Nations Environment Programme
UNFC	United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources
USA	United States of America
USD	US-Dollar
USDOE	U.S. Department of Energy
USGS	United States Geological Survey
VDI	Association of German engineers

WEEE	Waste electrical and electronic equipment
WGI	World governance indicator

Chapter 1 Introduction

1.1 Research context: why we need an accessibility evaluation

An increased number of (geochemically) scarce metals[1] are entering our daily lives via new technological applications (Zepf *et al.*, 2014). A reversal of this trend is not foreseeable, leading to concerns about security of supply. This has resulted in a 43.8% increase in the cumulative price of metals from 1974 to 2010, now known as the 'commodity super cycle' (Erten and Ocampo, 2013). For many scarce metals, including Neodymium (Nd) from the rare earth elements (REE) group, the raw material situation is considered critical for the following reasons (EC, 2014):

(i) The production of raw material is concentrated in a small number of countries (Simoni *et al.,* 2014); there are five main producing countries of REE (Wall, 2014), with the share of the largest producer (China) being 98% in 2010 and 68% in 2015 (Simoni *et al.*, 2015).

(ii) There are limited options for alternative materials that can substitute for many scarce metals without resulting in a loss in performance; the best substitutes for REE are within the same metal group and are therefore subject to the same supply risk as the target metal (Graedel *et al.,* 2013).

(iii) Recycling rates for these metals are very low; the REE recycling rate is <1% (UNEP, 2012).

To ease concerns about the supply situation of scarce metals and enhance resource efficiency through the closing of material cycles, novel raw material management approaches are required (Ongondo *et al.,* 2015).

One approach that is currently being discussed in Switzerland is the revision of the Ordinance on the Return, Take-Back and Disposal of Electrical and Electronic Equipment (ORDEE), which states that scarce metals will have to be recovered if possible with proportional effort. This will not only apply to waste electrical and electronic equipment (WEEE), but also to electrical and electronic equipment (EEE) in buildings and vehicles (FOEN, 2013). Prerequisites therefore are both the occurrence of scarce metals, i.e. their 'availability', and their 'accessibility'. Whilst the notion of 'availability' is well understood, an explicit and systematic scientific examination of 'accessibility' as a concept has not yet been provided. Currently, individual aspects of raw material accessibility have been implicitly included in studies of economic geology, for instance within different resource classification frameworks (Weber, 2013). These frameworks meaningfulness is depending on the availability of uniform definitions, and of knowledge about materials, technologies, environment, as well as society. An un-

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[1] (Geochemically) scarce metals are those metals, whose crustal abundance is <0.01 weight-% (Wäger *et al.*, 2012).

derstanding of limitations is also necessary for mining deposits in the anthroposphere[2] (MDA) (Brunner, 2011; Rankin, 2011; Wäger, Widmer and Stamp, 2011; M. U. Simoni, 2012; UNEP, 2012; Krook and Baas, 2013; Haines *et al.*, 2014). At present, only opaque and limited data exists pertaining to such approaches (Achzet and Helbig, 2013) and the evaluation of scarce metal management approaches is still in its infancy (Velis and Brunner, 2013).

1.2 PhD research objectives and scope

The aim of this study is to develop a structured methodological framework for characterising and evaluating the accessibility of scarce metals from EoL products and the Earth's crust under sustainability considerations. This study has three objectives, which are to:

(i) Develop a structured approach for a reconnaissance of anthropogenic deposits by means of geological characterisation and evaluation.
(ii) Build the fundamental knowledge, develop and initially apply a framework for characterising and evaluating accessibility for both EoL products and the Earth's crust.
(iii) Refine, confirm, consolidate and apply a structured methodology for characterising and evaluating accessibility for both EoL products and the Earth's crust.

The scope of this study is to evaluate 'accessibility' by considering interdisciplinary influences quantitatively at a macro system level. The developed methodology will adhere to the requirements of the upcoming ORDEE (FOEN, 2013), research concept environment for the years 2017 – 2020 (BAFU, 2016) and will fit the criteria of the UK Research Council Energy Program (UK Research Council, 2016). The study will focus on several selected case studies.

This study will also investigate the application of indicators[3] for characterising and evaluating the material efficiency of substance and material flows. Additionally, this provides an indication on measuring progress toward a green economy (BAFU, 2016). The understanding of indicators of material efficiency, with critical materials such as Neodymium and Europium (Moss *et al.*, 2013), is also important for securing energy supply (UK Research Council, 2016). Therefore, international partnerships are central to the exchange of knowledge and experience in tackling global raw material issues (UK Research Council, 2016). It is important to ensure that these research priorities are integrated into the development of a methodological framework that will be used in future.

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[2] The 'anthroposphere' includes the living space created and designed by people (Kosmol *et al.*, 2012).

[3] Statistical measures that are used to consolidate complex data into a simple number or rank that is meaningful to policy makers and the public (Merry, 2011).

1.3 Thesis structure

This study consists of seven chapters, with the main original work presented in Chapters 4 - 6. Each of these chapters contributes to the aim of this thesis. The thesis structure, gaps in scientific knowledge, objectives and research steps as well as resulting chapters are depicted in Figure 1. This thesis is structured as follows:

Chapter 1: provides the research context, PhD research objectives and scope. It further outlines the interconnections between the chapters and the overall structure of this report.

Chapter 2: encompasses a critical review, which in Section 2.2 investigates justifications for the scope of this research within evaluation steps among mining deposits in the anthroposphere and geosphere. It analyses first the geological evaluation and then builds correlating approaches to evaluate mining deposits in the anthroposphere. In Section 2.3 approaches for evaluating the typically well-understood notations of 'availability' and less well-understood notation 'accessibility' are critically reviewed.

Chapter 3: encompasses a methodological review for Chapter 4 to Chapter 6. It critically discusses, and justifies the use of the methods in this thesis. It then includes a description of the application of the methods in Chapter 4 to 6.

Chapter 4: presents 'a geological reconnaissance of electrical and electronic waste as a source for rare earth metals', which is a partially modified version of Mueller *et al.* (2015) in *Waste Management*. The content of this chapter attempts to fill the knowledge gap of developing a structural approach to geologically characterise and evaluate the anthropogenic deposits of EoL products (Stamp, 2014; Velis and Brunner, 2013). Therefore, it aims to shed light on the process chain from mining to waste management (Brunner, 2011; Wäger, Widmer and Stamp, 2011; Simoni, 2012; UNEP, 2012). In particular, both mining deposits of the geosphere (MDG) and MDA require knowledge about mineable deposits (Lederer, Laner and Fellner, 2014). In the study, a framework was developed that allows the establishment of analogies between geological and anthropogenic processes. Based on this framework, analogies between MDG and MDA are derived for the case of REE and used to identify the most concentrated deposits for three selected EoL products containing REE components[4]. The three identified deposits are characterised and evaluated with 'geological' approaches. The investigation of the three case studies provides the basis for Chapter 4.

Chapter 5: presents 'a framework for evaluating the accessibility of raw materials from end-of-life products and the Earth's crust', which is a partially modified version of Mueller *et al.* (2017) in

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[4] The parts that combine with other parts to form something bigger (Cambridge English Dictionary, 2016).

Waste Management. There is a lack of research concerning the resilient and quantitative evaluation of scarce metals (Stamp, 2014; Velis and Brunner, 2013). Consequently, this chapter attempts to fill this knowledge gap by presenting an investigation into the quantitative characterisation and evaluation of scarce metal accessibility under sustainability considerations. Among others, it characterises and evaluates the accessibility of three anthropogenic and one geological deposit in an initial application. This initial application in turn provides a solid foundation for Chapter 6.

Chapter 6: presents 'evaluating the accessibility of raw metals from end-of-life products and the Earth's crust under sustainability considerations: methodological framework refinement, confirmation, consolidation and application'. The content of this chapter attempts to bridge the knowledge gap of a more robust an interdisciplinary methodological framework that includes sustainability considerations but also technological, economic and regulatory components to quantitatively evaluate the accessibility of raw materials (adopted from Velis and Brunner, 2013; Hagelüken, 2014). Based on the reviewed existing quantitative approaches in the literature review and the extracted concept presented in Chapter 5; then, by means of a Delphi expert survey and quantification, interdisciplinary components and indicators were refined and confirmed. These selected indicators were consolidated in a methodological framework, which in turn was applied to four case studies.

Chapter 7: presents the discussion, conclusions and recommendations and future research. It is structured as these three sections. The first section includes a discussion of this thesis, then potential benefits and research limitations. The second section includes conclusions and recommendation. The final section includes four potential future research topics to round off this thesis.

For readability in this study, the components are highlighted with quotation marks and the subcomponents and indicators[5] are in bold.

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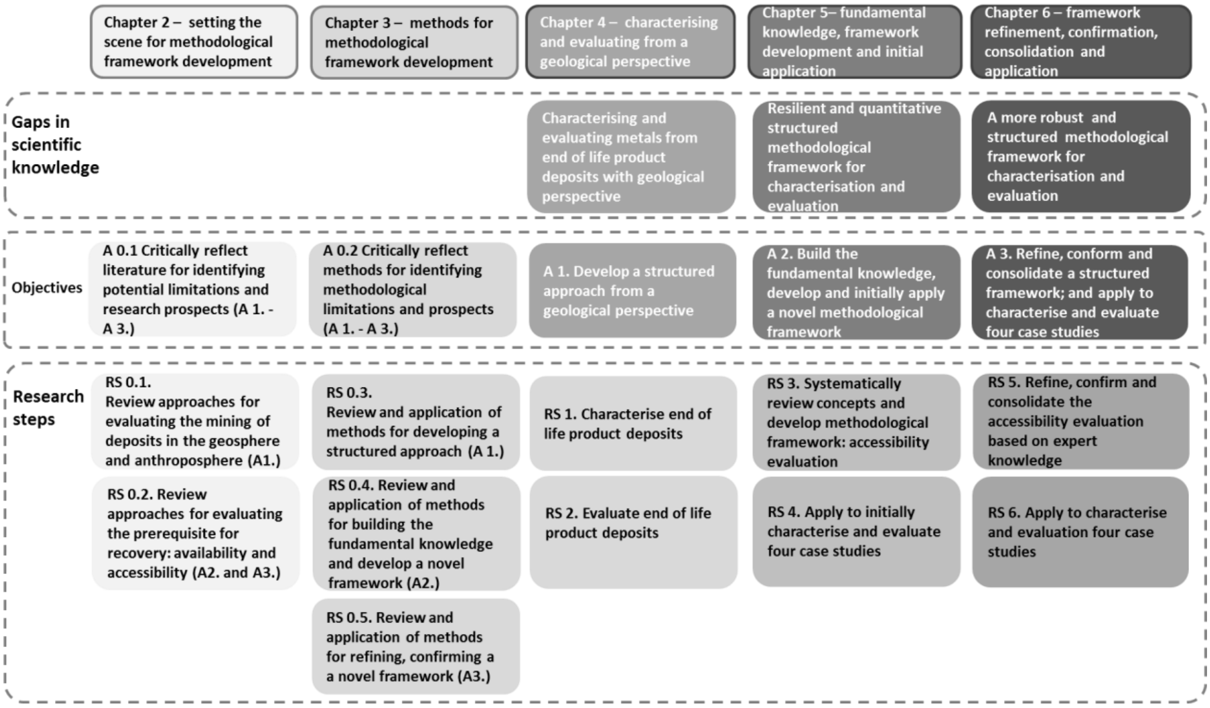
[5] Statistical measures that are used to consolidate complex data into a simple number or rank that is meaningful to policy makers and the public (Merry, 2011).



	Chapter 2 – setting the scene for methodological framework development	Chapter 3 – methods for methodological framework development	Chapter 4 – characterising and evaluating from a geological perspective	Chapter 5– fundamental knowledge, framework development and initial application	Chapter 6 – framework refinement, confirmation, consolidation and application
Gaps in scientific knowledge			Characterising and evaluating metals from end of life product deposits with geological perspective	Resilient and quantitative structured methodological framework for characterisation and evaluation	A more robust and structured methodological framework for characterisation and evaluation
Objectives	A 0.1 Critically reflect literature for identifying potential limitations and research prospects (A 1. - A 3.)	A 0.2 Critically reflect methods for identifying methodological limitations and prospects (A 1. - A 3.)	A 1. Develop a structured approach from a geological perspective	A 2. Build the fundamental knowledge, develop and initially apply a novel methodological framework	A 3. Refine, conform and consolidate a structured framework; and apply to characterise and evaluate four case studies
Research steps	RS 0.1. Review approaches for evaluating the mining of deposits in the geosphere and anthroposphere (A1.)	RS 0.3. Review and application of methods for developing a structured approach (A 1.)	RS 1. Characterise end of life product deposits	RS 3. Systematically review concepts and develop methodological framework: accessibility evaluation	RS 5. Refine, confirm and consolidate the accessibility evaluation based on expert knowledge
	RS 0.2. Review approaches for evaluating the prerequisite for recovery: availability and accessibility (A2. and A3.)	RS 0.4. Review and application of methods for building the fundamental knowledge and develop a novel framework (A2.)	RS 2. Evaluate end of life product deposits	RS 4. Apply to initially characterise and evaluate four case studies	RS 6. Apply to characterise and evaluation four case studies
		RS 0.5. Review and application of methods for refining, confirming a a novel framework (A3.)			

Figure 1: Overview of linking chapters with knowledge gaps, objectives, and research steps.

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Chapter 2 Literature review – setting the scene for methodological framework development

2.1 Linkage of chapter to PhD research

This chapter provides the theoretical foundation for all chapters in this thesis. It is structured as two main sections. The first section provides the foundation for Chapter 4 and the second addresses Chapter 5 and 6. The first section 2.2 critically reflects upon approaches for evaluating MDG and MDA. First approaches used to evaluate the MDG and then correlating approaches in MDA are reflected. On this basis, implications and potential limitations for MDG and MDA are drawn. Finally a gap in scientific knowledge is presented. In section 2.3, the foundation for evaluating the prerequisite for evaluating 'availability' and 'accessibility' is provided. First geological evaluation approaches are reflected, followed by supply chain evaluation approaches. Then, elements for evaluating the prerequisite 'availability' and 'accessibility' are critically discussed. On this basis, implications and potential limitations for evaluating 'availability' and 'accessibility' are investigated. Finally a gap in scientific knowledge is presented.

2.2 Approaches for evaluating the mining of the geosphere and anthroposphere

This section aims to establish at which step in the mining process the quantitative characterisation and evaluation of raw material should be performed. To address this aim, this section provides an overview of the steps involved in an evaluation of the mining of raw materials from the geosphere and the anthroposphere. An overview of the steps involved in MDG is then given, considering the steps from raw material exploration to metal production. In addition, the steps involved in evaluating raw materials are reviewed in detail. Parallel approaches for mining raw materials from MDA are discussed, highlighting how well established approaches in MDG could be applied to MDA.

To support a sustainable functioning of the EU an understanding of both the 'availability', and the 'accessibility' as well as a systematically measurable evaluation are required (Eurometaux 2010). Velis and Brunner (2013) summarise this by "*if you can't measure it, you can't manage it*". This study aims to develop a quantitative characterisation and evaluation by "*the transformation of an abstract, theoretical concept into something concrete, observable, and measurable in an empirical research project*" (Scott and Marshall, 2009).

The evaluation of MDG involves: reconnaissance, follow-up exploration and final 'evaluation' (Table 2). Then a decision on mine development is undertaken. If approved, the mine will be developed to mine crude ore. This is followed from mineral processing to obtain concentrates, which are smelted and refined into metals. This phase can take 10 to 20 years (Simoni, 2012). The technologies for mining have evolved rapidly over the last two hundred years (Arndt and Ganino, 2012). MDA have similar structured evaluation steps and influencing factors; Lederer, Laner and Fellner (2014) and Winterstetter *et al.*(2015) proposed that similar approaches to those used in the evaluation of potential mining sites of the geosphere are applied to evaluate potential mine developments in the anthroposphere. After a final decision on implementing mining is made, the processes followed include establishing a collection system; collection; dismantling; mechanical separation via metallurgical extraction and refining to the desired metal (Oguchi *et al.*, 2011). The influencing factors comprise governance, particularly the ownership, economics, technology and the potential environmental and social impacts (Giurco and Cooper, 2012; Sprecher *et al.*, 2015). Despite these similarities, there are differences. The MDA does not yet describe resources and reserves and does not employ a systematic pre-feasibility and feasibility study of a mine's development, unlike within MDG common practiced (Brunner, 2011).

To ascertain the 'availability' of a raw material, there are other examples that are not commonly practised in the MDA. The Committee for Mineral Reserves International Reporting Standards (CRIRSCO) developed a standardised classification framework for evaluating any mining intentions, to ensure that a common terminology and understanding is used in a quantitative raw material evaluation (CRIRSCO, 2008). The CRIRSCO was developed for considering the modifying factors and then assessing the viability of a mining project and determining whether or not the deposit will be exploited (Graedel, Gunn and Tercero Espinoza, 2014). The modifying factors include considerations for mining, metallurgy, economy, marketing, legislation, environment, society and government. They are fundamental for any mining classification (Pohl, 2011). These classification systems are used to ascertain the availability of a raw material (Gupta, 2003b). The long tradition in applying these classification systems indicates that the quantification of raw material 'availability' is well understood.

There are numerous other national classification systems currently in use (Vaughan and Felderhof, 2002), such as the American McKelvey resource classification (Long, DeYoung and Ludington, 1998) and the recent and globally harmonized United Nations Classification Framework for Fossil Energy and Mineral Reserves and Resources (UNFC, 2010). The UNFC consists of the three axes, namely: socio economic viability (E-axis), project status and feasibility (F-axis), and knowledge and uncertainty of a material, i.e. geological knowledge (G-axis). Since this section is concerned with the approaches to mining, which addresses the UNFC at the surface level; the UNFC evaluation approach is reflected upon in detail in the section on geological evaluation approaches 2.3.1. In the following subsections, the basic geological and analogous anthropogenic evaluation approaches are introduced.

Table 2: Compilation of approaches for the steps in mining deposits in the geosphere (MDG) with analogues steps in mining deposits in the anthroposphere (MDA) (adopted from Oguchi *et al.,* 2011). For the 'evaluation steps' the possible different evaluations and related UNFC classification axis are listed. In grey are the main stages and in italic the material states.

Geological approaches			**Anthropogenic approaches**	
Mining	**Evaluation**	**UNFC classification axis**	**Mining**	**Evaluation**
Earth's crust			EoL product at owners	
Evaluation steps				
Reconnaissance exploration on macro level	1) Conceptual study 2) Surface study (Marjoribanks, 2010; Hoatson, Jaireth and Miezitis, 2011; Pohl, 2011)	G-axis: knowledge and uncertainty of a material, i.e. geological knowledge (Winterstetter *et al.*, 2015, 2016b, 2016a)	Reconnaissance exploration on macro level	1) Conceptual study 2) Surface study (Brunner and Rechberger, 2004; Lederer *et al.*, 2016)
Follow-up exploration on micro level	1) Identification of potential ore body 2) Pre-feasibility study with (Marjoribanks, 2010; Pohl, 2011) - Quantitative resource assessment (Singer, 2010) - Quantitative impact assessment (Haines *et al.*, 2014)	G-axis: knowledge and uncertainty of a material, i.e. geological knowledge F-axis: project status and feasibility E-axis: socio and economic viability (Winterstetter *et al.*, 2015, 2016b, 2016a) er/csl-citation.json"} (Winterstetter *et al.*, 2015, 2016b, 2016a)	Follow-up exploration on micro level	1) Identification of potential ore body (Oguchi *et al.*, 2011; Widmer *et al.*, 2015) 2) Pre-feasibility study (Winterstetter *et al.*, 2015, 2016b, 2016a)
Final 'evaluation' aiming to classify geological resources into reserves	1) Detailed geological study 2) Feasibility study (Pohl, 2011): With classification	G-axis: knowledge and uncertainty of a material, i.e. geological knowledge F-axis: project status and feasibility E-axis: socio and economic viability (Winterstetter *et*	Final 'evaluation' aiming to classify anthropogenic resources into reserves	1) Detailed characterisation (Hagelüken, 2014) 2) Feasibility study with LCA, detailed cost evaluation, etc.

Geological approaches			**Anthropogenic approaches**	
Mining	**Evaluation**	**UNFC classification axis**	**Mining**	**Evaluation**
		al., 2015, 2016b, 2016a)		
		'Mining' operation		
Mine development			Collecting, recycling system development	
Mine			*Selected EoL products for collection*	
Ore mining			Collection	
Crude Ore			*Collected EoL products*	
		Processing		
Mineral processing			Sorting, dismantling, mechanical separation	
Concentrates			*Concentrates*	
Metallurgical extraction, refining			Metallurgical extraction, refining	
Metal			***Metal***	

2.2.1 Approaches for evaluating the mining of the geosphere

The first process in a search for a deposit is the exploration stage (Pohl, 2011) (Table 2). This resource evaluation is used to investigate the viability of a mine (Graedel, Gunn and Tercero Espinoza, 2014) such that the raw material will become accessible. Since the exploration process can take 1-3 years and involve high investments (Rankin 2011), a geologist must follow a scientific and systematic procedure that increases access to viable mine development projects (Marjoribanks, 2010). Exploration projects are investments for enterprises and therefore require clearly defined and constantly updated cost-benefit analyses and risk assessments (Pohl, 2011). For example, in 2008 the worldwide exploration of non-ferrous metal and industrial mineral projects accounted for 14,400 million USD (US Dollar). This emphasises that exploration is the most expensive and time consuming step. In particular the drillings are costly (Marjoribanks, 2010). Additionally, monitoring, reporting and evaluation of impacts on environment and society have to be undertaken from the beginning. It is central to commence these impact studies as early as possible, in order to avoid unexpected costs (Pohl, 2011). Haines *et al.* (2014) highlight that for sustainable mining, the integration of external benefits and costs of impacts have to be a prerequisite. Importantly, at the end of each 'evaluation step', raw materials are often consolidated and reported according to the CRIRSCO and the UNFC classification framework. A review of the exploration process can be found in the following subsections.

Evaluation of geological mine: reconnaissance exploration. In this phase, a macro-level investigation is carried out, involving the collection, modelling and interpretation of existing geological knowledge and maps (Pohl, 2011). The interpretation of geological knowledge can include an evaluation according to the UNFC classification framework at the G-axis. This includes estimations of recoverable raw material quantities and its level of confidence (United Nations, 2013). It also involves the compilation of existing information of potential impacts on society and the environment, which is often neglected (Corder, McLellan and Green, 2010; Haines *et al.*, 2014). An example for overcoming this neglect is the current expansion of the UNFC's social and environmental viability (UNFC, 2017a).

The generation of new prospects[6] is an important stage and involves Earth surface observations for indications of mineralisation and initial drillings to identify the target (Marjoribanks, 2010). During this stage, there is an exponential decline in the number of prospects; this means most mining intentions are rejected. It becomes even more important to apply a characterisation and evaluation with a clear methodological description as applied by such as Dill (2010); and Hoatson, Jaireth and Miezitis (2011). The results of this phase provide an approximate understanding of the potential resource[7].

Evaluation of geological mine: follow-up exploration This encompasses extensive and systematic data collection and exact modelling of the prospect area (Lederer, Laner and Fellner, 2014). Hence, a detailed understanding of geological processes is essential. Models commonly used today are typically four-dimensional, i.e. three-dimensional area models that also include a temporal dimension. These models will be complemented with data about geology, geophysics, geochemistry and drill holes, e.g. size, shape, depth, mineralogy, fluid flow and deformation information with its anomalies.

The drilling step can be considered as a second critical stage of exploration, because decisions on rapidly increasing investments have to be made. These decisions may mean that other prospects will be suspended for a long period (Marjoribanks, 2010). For potential locations, a pre-feasibility study is carried out. This involves more drilling to initially estimate a mine's potential, which leads to determining its economic prospects by means of comparing this mine with similar existing mines (Pohl, 2011). To integrate a continuously applied and viable sustainability assessment[8], it is recommended to apply standardised methods, such as determining impacts on water, carbon emission, habitats or society (Haines *et al.*, 2014). The follow up exploration can be reported, evaluated and classified with

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[6] The prospect is a restricted volume of ground that is considered to have the possibility of directly hosting an ore body and is usually a named geographical location (Eurometaux, 2010; Marjoribanks, 2010).

[7] A resource is a natural concentration of minerals or a body of rock that is, or may become, of potential economic interest as a basis for the extraction of a mineral commodity (European Commission, 2010).

[8] A complex evaluation method in a broad environmental, economic and social context.

the UNFC classification framework. This information regarding the three axes, E, F, G, and the estimated quantities need to be consolidated and reported (Lax *et al.*, 2017). The exploration is terminated when projects are selected for a detailed evaluation (Lederer, Laner and Fellner, 2014; Rankin, 2011).

Evaluation of geological mine: final 'evaluation'. The aim of this evaluation step is to provide comprehensive knowledge of the ore body in the deposit that enables mining companies and authorities to make a final decision about a mine development project. This includes mine exposures to test the physical feasibility of ore processing (Pohl, 2011), the required processing plant and infrastructure and a feasibility study (Marjoribanks, 2010; Pohl, 2011). Thereby, investment and operating costs, revenue estimation (Pohl, 2011) and uncertainty modelling (Haines *et al.*, 2014) are performed. Potential impacts on the environment and society are estimated via evaluations, such as Life Cycle Assessment (LCA) or the Policy Potential Index (PPI). The latter gives a report card to governments on how attractive their policies are from an exploration manager's point-of-view (Graedel *et al.*, 2012). Haines *et al.,* (2014) argue that sustainability impact analysis should be considered of equal importance as the currently applied material availability quantification. To obtain authorisation for conducting an exploration project, social conditions are becoming increasingly important, which include (non-exclusively) the local population's acceptance of the mining project and the long-term political stability of a region (Pohl, 2011). The final 'evaluation' can be consolidated and reported with the UNFC classification framework (Lax *et al.*, 2017) as with the follow up exploration.

2.2.2 Correlating approaches for evaluating the mining of the anthroposphere

For MDA, Lederer, Laner and Fellner (2014) proposed a framework for the evaluation of anthropogenic resources that is analogous to the evaluation of resources from MDG. Graedel, Gunn and Tercero Espinoza (2014) describe approaches on how geological mining is explored and evaluated, whilst Oguchi *et al.* (2011) highlight how MDG can be correlated with MDA. For this, it is recommended to develop a commonly-agreed upon terminology, as generally implemented in mining the Earth's crust (Winterstetter *et al.*, 2015). To identify the most promising anthropogenic mine for an evaluation, Johansson *et al.* (2012) introduced a novel approach for mining the technosphere based on a new taxonomy. This taxonomy aims to provide a comprehensive and consistent definition of the technosphere and thereby creates opportunities for new business models and policy instruments. This concept divides technosphere mining into six classes (Figure 2).

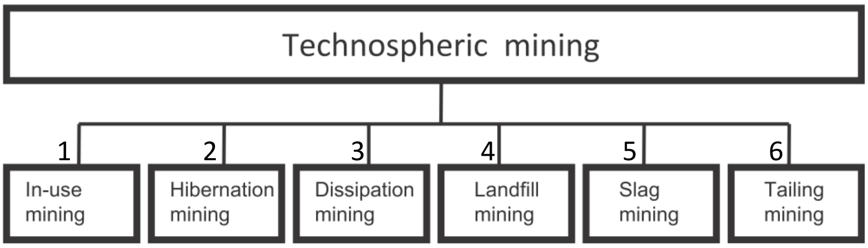

Figure 2: Illustration of the technosphere mining into six different mining types (adopted from Johansson et al., 2012).

This approach clearly divides the different mining sectors but maintains the traditional view on stocks, which represent significant potential for recovery. However, geological mine evaluation does not initially distinguish between different types of mines, it rather explores all possible options and only continues the prospects with the greatest potential for exploitation. However, any mining project must include impact studies on the environment and society as well as resource conservation (Brunner, 2013).

In the following subsections, approaches of geological evaluations are transferred and linked with potential anthropogenic evaluations. A particular emphasis is laid on identifying a possible positioning of evaluating the accessibility of scarce metals.

Evaluation of anthropogenic mine: reconnaissance exploration. Similar to geological mining, it is important to carry out a macro-level study that consists of a desk study for characterising and evaluating a predefined location, such as a country (Lederer, Laner and Fellner, 2014), city (Lederer *et al.*, 2016). This investigation shall address both regional and global mining benefits and limitations equally (Velis and Brunner, 2013). The characterisation should include a material flow assessment (MFA) (Brunner and Rechberger, 2004) and a description of the spatial location and its included materials (Jaireth, Hoatson and Miezitis, 2014), such as ore (Oguchi *et al.*, 2011) or EoL products (Wäger *et al.*, 2012). The characterisation should also include an investigation of the current recovery system to utilise synergies (Oguchi *et al.*, 2011). As in geological reconnaissance exploration, secondary data on the impacts on the environment and society should be collected. This is especially important for harmful impurities and deleterious substances, which is often lacking (Haines *et al.*, 2014). The evaluation could include a classification by means of the UNFC classification's G-axis, as applied by Winterstetter (2016). Winterstetter characterised and evaluated the resource potential from landfills, wind turbines and obsolete computers.

Evaluation of anthropogenic mine: detailed exploration. For a detailed exploration i.e. micro-level study, a characterisation and evaluation is implemented. The characterisation includes an identification of the 'ore body' as carried out by Funari *et al.*(2015), Oguchi *et al.*(2011), and Widmer *et al.*(2015). This consists of chemical analyses of potentially mineable metals. Similarly, Ongondo, Williams and Whitlock (2015) emphasised that it is important to assess hotspots, i.e. potential distinct urban mines, to facilitate selective and separate collection of high value EoL products for maximum material resource exploitation. Because of the current lack of existing data on scarce metals such as REE, Simoni *et al.,* (2015) suggest that the spatial scope should be positioned at a national level.

On this basis, a pre-feasibility study needs to be carried out. This should comprise of an initial investigation into the economic viability of mining a deposit through a combined technology, governance and a standardised sustainability assessment (Haines *et al.*, 2014). Within the economic viability assessment, the added value of recycling should be determined though net present value (Winterstetter *et al.*, 2015). This includes comparisons to alternative recycling options or projects (Velis and Brunner, 2013). The evaluation could include a consolidation and reporting through the UNFC classification framework (Winterstetter, 2016).

Evaluation of anthropogenic mine: final 'evaluation'. A detailed characterisation and evaluation of the proposed recovery system is required. The characterisation should include demonstrating large scale production (Hagelüken, 2014) and will provide the basis for a detailed feasibility study, which should include the investments, operating costs and revenues. The evaluation can include the UNFC classification (Winterstetter *et al.*, 2016b). Winterstetter *et al.* (2014) have implemented a detailed economic evaluation study of landfills. Their initial evaluation showed that for landfill mining without subsidies or other financial incentives, revenue would be negative. This is tackled by investigating external costs such as environmental impacts.

Moreover, a detailed assessment on sustainability impacts should be conducted, which could include LCA (Kulczycka *et al.*, 2016). To provide a comprehensive understanding of sustainability, this assessment should describe the ecology, technology, economy, government and society as carried out by Simoni, Kuhn and Adam (2014).

2.2.3 Implications and potential limitations for evaluating the mining of the geosphere and the anthroposphere

Cuddington (2008) was one of the first publications that explicitly emphasized the development of analogies between MDG and MDA. Subsequently, the publications of Oguchi *et al.* (2011) and Winterstetter *et al.* (2016) represent positive steps in enhancing the understanding of, and providing initial steps toward a common understanding of mining issues. These can include the 'evaluation steps' for both MDG and MDA. The research of Oguchi *et al.* (2011) highlighted and implemented an application of key analogies, such as characterization of MDA by means of approaches from MDG.

Winterstetter (2016) implemented exemplary applications of analogies and demonstrated their benefits, while identifying, characterizing, and evaluating three case studies from MDA based on the UNFC classification framework. With these classifications, Winterstetter (2016), showed concrete potential for actions regarding MDA and helped to prioritise the needs and incentivises for further research on MDA. Winterstetter even inspired the launch of new activities, such as the COST action network: MINEA (Kral, 2015). The research outcomes of Oguchi *et al.,* (2011) and Winterstetter *et al.,* (2016) include innovative results and provide a basis for developing analogies, such as characterization and evaluation of raw materials based on economic geology. However, the limitation of their research in this area was underlined by the lack of consideration regarding geological processes initiating from the physical crustal movements and subsequently employing a uniform set of indicators (Velis and Brunner, 2013). This must be taken into account in future research. Definitive conclusions about the resulting characterisation and evaluation cannot be drawn,as their results are the first applications of this kind.

A wide number of potential analogies, such as processes from geology, waste management and the MINEA activities have shown large interest not only in the waste management community but also with geologists. However, little research has been carried out on the early project development stage, in particular for scarce metals (Velis and Brunner, 2013).

The impact of this research could be considerable given the initial application, and their findings could influence many researchers as well as public understanding regarding how anthropologic raw materials are characterised and evaluated. These are important issues, which could have profound effects on the advancement of MDA by applying a geological perspective.

2.2.4 Gap in scientific knowledge for evaluating the mining of the geosphere and the anthroposphere

Mining approaches for characterising and evaluating are established in MDG but limited for MDA (Lederer, Laner and Fellner, 2014). Consequently, these approaches are not fully suitable as a basis for policy recommendations. Rather they should serve as a first step in identifying systematic analogies in the ‘evaluation step’, namely reconnaissance exploration between MDA and MDG. Such a reconnaissance exploration should involve characterisations and evaluations (Velis and Brunner, 2013). Ten years ago, analogical approaches such as geological characterisations and evaluations on MDA were starting to be established and advocated a close collaboration of experts to systematically develop and apply characterisations and evaluations between MDA and MDG. These remain challenges today.

During the early project development stage, there is a need to fill the knowledge gap of developing a structural approach to geologically characterise and evaluate the anthropogenic deposits of EoL products (Stamp, 2014; Velis and Brunner, 2013). This includes evaluating raw materials with the UNFC classification at the G-axis (Winterstetter, 2016) (Table 2).

This is particularly promising, since researchers from TU Vienna were first encouraged by the 'Expert Group on Resources Classification of the United Nations Economic Commission for Europe' and then later asked by Helmut Rechberger [Technische Universität Wien, Austria] to form a pan-European Network on MDA to develop specifications for the applications of the UNFC classification to anthropogenic resources. This specification is now in its final draft development stage (Kral, 2015). Therefore, it is important to shed further light on the process chain from mining to waste management (Brunner, 2011; Wäger, Widmer and Stamp, 2011; Simoni, 2012; UNEP, 2012).

2.3 Approaches for evaluating the prerequisites for recovery: availability and accessibility

Prerequisites for the recovery of a raw material are its occurrence and its retrievability, which is determined based on two factors: its 'availability' and 'accessibility'. The concept of raw material availability is well established, understood and applied, see sections 2.3.1 and 2.3.2. Hence, this section is chiefly concerned with the concept of raw material availability, and how the established approaches for evaluating material availability could be applied to evaluate the accessibility of a raw material and narrow the scope. Two overarching evaluative approaches were considered: geological and 'supply chain' approaches. The former can be linked to identifying the 'degree of available' raw material (Gupta, 2003b) and partially specifying indicators. The latter concerns the quantification of components and specifying indicators, which influence the raw material availability along the supply chain (Graedel and Reck, 2015). It becomes apparent, since there is a diversity of evaluation approaches, there is not yet an ideal approach. Moreover, it becomes possible to develop a methodological framework that has the greatest validity and the most widespread support (adopted from Graedel and Reck, 2015).

To explore the properties and variations of availability approaches, the following 16 different approaches were identified for reviewing. They evaluate both mining the MDG and MDA and their principal characteristics. To integrate evaluation approaches originating from MDG, this review includes the McKelvey Resource Classification (Weber, 2013); UNFC (UNFC, 2010, 2016), the current expansion on the socio-environmental consideration (UNFC, 2017a). These approaches are widely applied, globally implemented and transferred to MDA (Lederer, Laner and Fellner, 2014; Winterstetter *et al.*, 2015). This was complemented with a recent evaluation approach, the 'multi-dimensional methodology supporting a safeguarding decision on the future access to mineral resources' (Mateus *et al.*, 2017). For a broad foundation, this review includes criticality evaluations, dynamic supply chain evaluations and global reporting initiatives. The global reporting initiatives were added, since these initiatives use consistent evaluation aspects (Elliott, 2015). The following evaluations were considered: minerals, critical minerals and the U.S Economy (NRC, 2008); material security (Oakdene Hollins, 2008); critical raw materials for the EU (EC, 2014); critical raw materials for the EU (EC, 2017a); Risk List 2015 (BGS, 2015); sustainable resource strategies in corporation (Tuma *et al.*, 2014); metal criticality determination, national level (Graedel *et al.*, 2012); critical metals towards a decarbonisation of the EU Energy Sector (Moss *et al.*, 2013); cumulated raw material effort VDI 4599 (Neugebauer, 2013); resilience in material supply chains (Sprecher *et al.*, 2015); RESCHEK (Spörri *et al.*, 2017); GRI standard (GRI, 2016a, 2016b, 2016c); SCARCE method: critical resource use of Germany (Bach *et al.*, 2017). The review of Graedel and Reck (2015) was excluded, because it is outdated (Frondel *et al.*, 2006; EC, 2010) and had too narrow of a metal specific focus and did not apply a broad perspective (Buchert, Schüler and Bleher, 2009; Rosenau-Tornow *et al.*, 2009; Duclos, Otto and Konitzer, 2010; USDOE, 2011; Achzet and Helbig, 2013; Zepf *et al.*, 2014; Helbig *et al.*, 2016). An exception was made to the energy sector (Moss *et al.*, 2013; Sprecher *et al.*, 2015), due to their dynamic modelling considerations. Also, this means all other reviewed methods are a snap shot in time. For a detailed systematic review, see 0.

It is useful to first provide an overview on the evaluative approaches, as in Table 3, and then a more detailed description of the different methods, as in section 2.3.1 and 2.3.2. Subsequently, this section provides a systematic review to narrow the scope for the anticipated research on quantifying accessibility in section 2.3.3. It then provides the wider implication and concludes with future research recommendations.

Table 3: Overview on reviewed approaches that evaluate the pre-requisite of recovery: availability. They are divided in approaches related to mining deposits in the geosphere and anthroposphere.

No	Name	Subject field	Scope	Components	Uniqueness	Reference
Mining deposits from the geosphere (MDG)						
MDG 1	McKelvey Resource Classification	geology	resource classification	- geological assurance - economic / technological feasibility	- first common classification system and nomenclature (Poroskun *et al.*, 2004)	(Long, DeYoung and Ludington, 1998)
MDG 2	The United Nation Classification Framework for Fossil Energy and Mineral Reserves and Resources 2009	geology	resource classification	- socio-economic viability (axis E) - project feasibility (axis F) - geological knowledge (axis G)	- globally harmonised resource classification system - specifications are being developed for classifying anthropogenic resources	(UNFC, 2010)
MDG 3	Multi-dimensional methodology supporting a safeguarding decision on the future access to mineral resources	geology	resource assessment	- level of Geological Knowledge - Economic - Environmental - Social Development and Acceptance	- geological knowledge in an evaluation apart from resource classifications - specific indicators used	(Mateus *et al.*, 2017)
Mining deposits from the anthroposphere (MDA)						
MDA 1	Minerals, critical minerals and the U.S Economy	anthroposphere	criticality evaluation	- supply restrictions - availability / supply risk	- one of the first criticality studies and spatial focus: country level - development with experts inputs	(NRC, 2008)
MDA 2	Material Security, ensuring resource availability for the UK economy	anthroposphere	criticality evaluation	- material risk - supply risk	- one of the first criticality studies and spatial focus, i.e. a country level - focus on indicators result for critically evaluation (rather than one aggregated total score).	(Oakdene Hollins, 2008)
MDA 3	Critical materials for the EU	anthroposphere	criticality evaluation	- economic importance - supply risk /	- Evaluation repeated every three years (including	(EC, 2014, 2017a)

No	Name	Subject field	Scope	Components	Uniqueness	Reference
				poor governance	method development with large pool of experts) - large spatial level: continent	
MDA 4	Risk List 2015	anthroposphere	criticality evaluation	- supply risk	- concise supply risk evaluation (as part of criticality evaluation)	(BGS, 2015)
MDA 5	Critical metals towards a decarbonisation of the EU energy sector.	anthroposphere	criticality evaluation	supply chain with focus on - market and - geopolitical factors	- specific sector: low-carbon energy technologies	(Moss *et al.*, 2013)
MDA 6	Metal criticality determination.	anthroposphere	criticality evaluation	- supply risk - vulnerability to supply restrictions - environmental implication	- explicit integration of environmental implication as a first criticality study - broad list of indicators.	(Graedel *et al.*, 2012)
MDA 7	Sustainable resource strategies in corporations	anthroposphere	criticality evaluation	- economy - ecology - society	- company level evaluation - development with expert survey and the AHP method. - integration of component society as the first criticality study	(Tuma *et al.,* 2014)
MDA 8	Cumulated raw material effort VDI 4599	anthroposphere	criticality evaluation	- relative scarcity, respectively availability - environmental implications	- development from an engineering society	(Neugebauer, 2013)
MDA 9	Integrated sustainability assessment for production and supply of raw material and primary energy carriers.	anthroposphere	criticality evaluation	- environment - economy - society - technology	- broad evaluation approach of the subjects: environment, economy, society and technology	(Dewulf *et al.*, 2015)
MDA 10	SCARCE method: critical resource	anthroposphere	criticality evaluation	- economy for criticality	- enhancements of criticality evalua-	(Bach *et al.*, 2017)

No	Name	Subject field	Scope	Components	Uniqueness	Reference
	use of Germany			- society - environment	tion with societal acceptance (includes compliance with social and environmental standards) on country level	
MDA 11	RESCHECK resource criticality evaluation of scarce metals for small and mediums size companies	anthroposphere	criticality evaluation	- supply risk - vulnerability to supply restrictions - environmental implications - social implications	- criticality evaluation of scarce metals for small and medium-sized enterprises - Explicit integration of components addressing environmental and social implication	(Spörri *et al.*, 2017)
MDA 12	Resilience in metal supply chain	anthroposphere	system understanding		- focus on dynamic evaluation	(Sprecher *et al.*, 2015)
MDA 13	GRI: Gri 307: Environmental Compliance, 2016, Gri 103: Management Approach, 2016, Gri 419: Socioeconomic Compliance, 2016	anthroposphere	company performance evaluation	- economy - society - environment	- application for evaluating the sustainability consideration on company level in both mining deposits in the geosphere and anthroposphere	(GRI, 2016a, 2016b, 2016c)

2.3.1 Geological evaluation approaches

In geology, raw material availability is evaluated by means of classification, which evaluates the mining viability (USDOE, 1996). There are two main forms of classification and a recent multi-dimensional method, which are discussed in the following: '*McKelvey Resource Classification*' (Long, DeYoung and Ludington, 1998), the '*United Nation Classification Framework for Fossil Energy and Mineral Reserves and Resources* (UNFC)' (UNFC, 2010), and '*Towards a multi-dimensional methodology supporting a safeguarding decision on the future access to mineral resources*' (Mateus *et al.*, 2017).

MDG 1. McKelvey Resource Classification. In 1976, the United States Geological Survey (USGS) developed the first globally common classification system and nomenclature (Poroskun *et al.*, 2004). After many revisions, a means of classification via the McKelvey diagram emerged (Figure 3). This diagram differentiates between geological assurance and economic / technological feasibility and assigns the deposits as resources, reserves or undiscovered (Long, DeYoung and Ludington, 1998). The framework depicted in Figure 3 has been widely used by geologists and economists to evaluate the resource base, which provides central knowledge on the continuation of a product (Skinner, 2001). The advantages of this approach are a concise overview on the process of mining a deposit. The disadvantages include project feasibility not explicitly assigned in this classification.

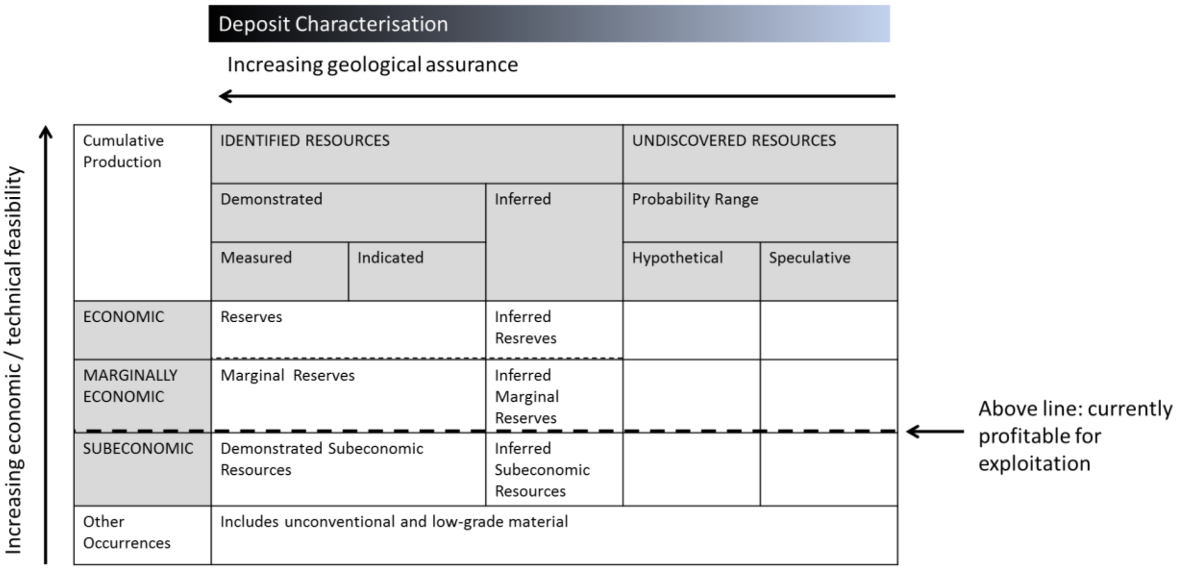

Figure 3: McKelvey Resource Classification, illustrating the classification of resource and reserve relationship of ore with the encompassing concept of deposit characterisation. Adopted and redrawn from Long, DeYoung and Ludington (1998).

MDG 2. The United Nations Classification Framework for Fossil Energy and Mineral Reserves and Resources (UNFC). In 2009, a global classification framework was published by the United Nations with the aim of developing a single uniform classification system (UNFC, 2010). This system classifies the resources according to three categories: socio-economic viability, project feasibility and geological knowledge (Figure 4). The scheme is divided into seven classes: commercial projects, potentially commercial projects, non-commercial projects, exploration projects, additional quantities in place, other combinations and extracted quantities, comprising of sales and non-sales production. Recent developments includes suggesting a nomenclature of the UNFC for a wider scope; evaluating the naming of the G-, E-, and F- axis; and recommending updates to the principles of the UNFC to make it more generic and applicable (UNFC, 2017b). The further development of environmental and social consideration includes *inter alia* the adaption of the name 'economic viability' to 'commercially viability' and adding a new subclass on classifying environmental and social issues that have to be resolved, namely E2.2 (UNFC, 2017a). It further defines the terms environmental, social, and political contingencies and the social license to operate (UNFC, 2017a). Moreover, draft guidelines on how to classify anthropogenic resources were established, presented and well perceived from the UNFC committee. This specification was developed in accordance with existing guidelines, namely UNFC, renewable energy specifications, geothermal energy specifications and uranium and thorium resource guidelines. This new specification provides definitions for inter alia the anthroposphere, anthropogenic material system (Heuss-Aßbichler *et al.*, 2017). Overall, this framework evaluates the availability of raw materials in geological deposits (USDOE, 1996). The advantages of this approach includes an easy communication tool for stakeholders and being published under the umbrella of the UN. The disadvantages include evaluating the potential contradictory aspects on society and economy in one axis.

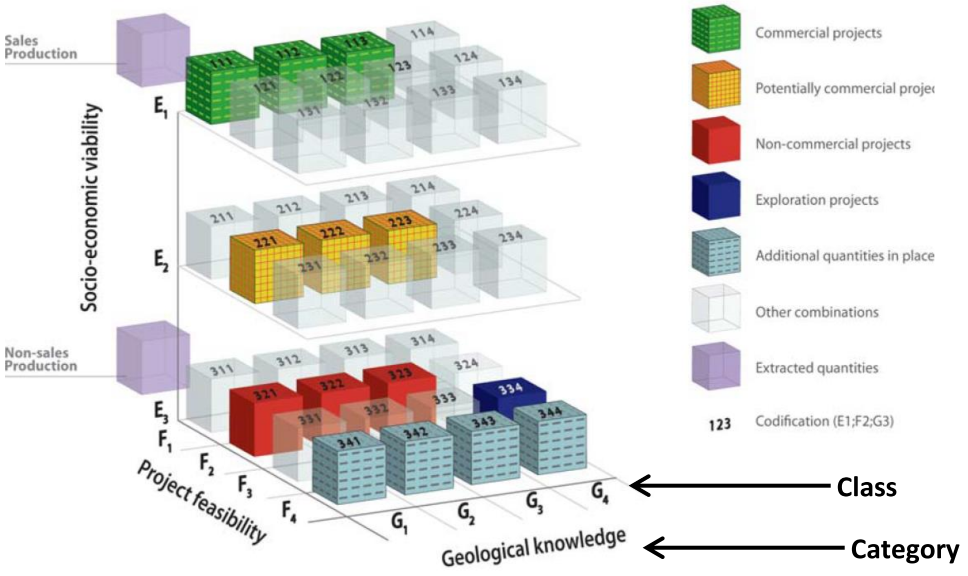

Figure 4: Categories and examples of classes on how to evaluate resources and reserves (Reproduced courtesy of the United Nations Economic Commission for Europe and adopted from (United Nations, 2013).

MDG 3. Multi-dimensional methodology supporting a safeguarding decision on future access to mineral resources. This evaluation approach aims to identify the areas that host mineral resources of public importance. The components comprise the level of geological knowledge, economic, environmental, and social development and acceptance dimensions. Each component has four to seven quantitative indicators that are multiplied with a semi-quantitative data quality assessment. This approach uses a weighting. The level of geological knowledge is weighted with 1.5 and other components as 1. Geological knowledge is more important since it is considered as a prevailing aspect for safeguarding future access / use of a mineral resource. The scope comprises country level and aggregation as a sum. The final scoring lies between 1 and 10, which corresponds with the 'McKelvey diagram' through the 'geological confidence' axis (Mateus *et al.*, 2017). There was no information on how the approach was developed, but this approach is an outcome of the MINATUA2020 project. The advantages of this approach are comprehensiveness and ease of practical applicability. The disadvantages include not being useful for a quick investigation, as it requires extensive knowledge on the local situation.

2.3.2 Supply chain evaluation approaches

A number of different approaches have been developed for evaluating the availability of raw materials along the supply chain. For this, 13 studies were selected; see overview of approaches MDA 1 – MDA 13 in Table 3 and discussion in section 2.3.3.

MDA 1. Minerals, critical minerals and the U.S Economy. The National Research Council (NRC, 2008) developed an evaluation approach that aims to understand the non-fuel mineral importance of a nation's economy and functions before a crisis occurs. This evaluation is based on criteria including the impact of supply restrictions and availability / supply risk. In this evaluation, 'availability' is understood as a surrogate with supply in relation to 'supply risk'. The impact of supply restriction addresses the importance of different minerals or materials. It is aggregated by multiplying the proportion of the total U.S. market for mineral 'x' with the impact of supply restrictions. The availability / supply risk reflects geological, technological, social, environmental, political and economic considerations as well as supply reliability and its risk. This approach is aggregated to the final score by the maximum single availability score. This approach was developed with an expert committee that met three times in the following setting: first with a partially closed group meeting with the sponsors and the federal agency, then in a public meeting and finally in a closed session to review the recommendations and draft the evaluation. The final result is scored between 1 (low) to 4 (high) for both axis criteria. As benefits, this evaluation can be used to investigate different applications in relation to the differences between short and medium-long term supply risk. However, as a limitation this approach might be biased by sponsors, since in the first committee meeting the sponsors were explicitly invited.

MDA 2. Material Security, ensuring resource availability for the UK economy. This approach aims to address the materials security of the UK. It includes two axes: material risk and supply risk. The material risk includes the indicators: global consumption, substitutability, global warming potential and total material requirements. The supply risk includes the indicators: scarcity, supply monopoly, political stability and vulnerability. 'Availability' is used in text headings, which give a direct indication about the content of the main text body (Weinhofer, 2010). This means, 'availability' can be understood as an overarching term that includes both material risk and supply risk. This evaluation was developed based on determining the criticality of materials (Graedel, 2007). However, little information on the development process is provided. The final result of each indicator is scored between 1 (low) to 3 (high), not focusing on an aggregated score. This evaluation's benefits include the evidently presented outcome of all 8 indictors; consequently each indicator's influence remains transparent until the final outcome. However, its limitations comprise the inclusion of qualitative judgements and little information about the development process and method description (Oakdene Hollins, 2008).

MDA 3. Critical materials for the EU. This approach aims to build a criticality analysis of the materials used in the EU. This approach was developed in 2011 and revised in 2014 and 2017. In the 2014 and 2017 evaluation, this approach consisted of two axes: economic importance and supply risk / poor governance. The economic importance includes the indicators: end uses of raw material and gross value added of European end use 'megasector'. The supply risk / poor governance includes the indicators: substitutability; EoL recycling rates; high concentration of producing countries with poor governance. 'Availability' is used in various contexts. One 'availability' use comprises the geological availability of a raw material in the supply risk. Another 'availability' use is 'the material availability to the EU'. This approach was developed by means of an *ad hoc* working group: EU Commission. This group comprises representatives from different member states, the extractive industries, intermediate user (e.g. steel), downstream industries, recycling industry, academia, and geological surveys, and consultants. The benefits include the development in collaboration with a large and diverse group of experts, the inclusion of the different 'megasectors' from the EU. However, the limitations contain the complex estimation of the final aggregated criticality score, the exclusion of the indicator environmental impact determination, and the partial use of qualitative indicators (EC, 2014, 2017a).

MDA 4. Risk List 2015. The aim of this approach is to update the risk evaluation of 41 elements and element groups for the British economy and lifestyle. It employs the indicators: i) production concentration, ii). reserve distribution, iii) recycling rate, iv) substitutability, v) governance (top producing nation), vi) governance (top reserve-hosting nation) and vii) by-product metal fraction. 'Availability' is used as an overarching term. The final result is scored between scoring: 1 (low) to 3 (high). The benefits comprise: transparent indicator description, calculation, aggregation and integrating publicly available data. However, the limitation includes no information regarding evaluation approach development (BGS, 2015).

MDA 5. Critical Metals towards a decarbonisation of the EU Energy Sector. This approach builds on the criticality evaluation in 2010 and aims to identify the critical metals for the supply chain of low-carbon energy technologies. The two axis criteria comprise market and geopolitical factors. The market factors include the indicators: limitations to expanding supply capacity and likelihood of rapid global demand growth. The geopolitical factors include the indicators: cross-country concentration of supply and political risk related to major supplying countries. 'Availability' is used and understood at a system level in relation to 'material' for the EU society. To develop this approach, various experts from the industry, governance and research were consulted (Moss *et al.*, 2013). However, there is no detailed description on the method development. Its benefits comprise a detailed analysis of raw materials as well as industrial applications and an indication of the lack of other criticality studies as well as suggestion to implementat a more dynamic assessment. However, its limitations include little information about the development process and methodology development.

MDA 6. Metal Criticality Determination. This approach aims to evaluate the metal criticality in three aggregated dimensions: i) supply risk, which is concerned with technological and economic, social and regulatory and geopolitical issues; ii) vulnerability to supply restrictions, which concerns the importance and substitutability of a material and its ability to innovate; and iii) 'environmental implication', which is quantified using the ReCiPe end point method for Life Cycle Impact Assessment (Tillman and Baumann, 2004). At present, all indicators are weighted equally and scaled to a range from 0 to 100 to allow flexibility for different units and users requirements. This approach is developed in collaboration with corporations, government consultants and researchers (Graedel *et al.*, 2012). This approach's benefits include an explicit inclusion of environmental implications, linear aggregation, its transparency, inclusion of different spatial resolutions: global, national and corporation, and detailed uncertainty description. Its limitations include lack of existing data, which remain of poor quality (Weber, 2013).

MDA 7. Sustainable resource strategies in corporations. Recently, a comprehensive approach particularly for technology-oriented small and medium sized enterprises, entitled 'Sustainable resource strategies in corporations: Identification of critical raw material and development of suggested action measures for implementation of a resource efficient production', was developed at the University of

Augsburg in Germany (Tuma *et al.*, 2014). This approach may be used to investigate the availability of raw materials in product components and comprises of a three dimensional evaluation of impacts related to the economy, ecology and society. The economic dimension includes the indicators: 'risk of concentration', 'political risk', 'risk of supply restrictions' and 'risk of demand increase'. The ecological dimension includes the indicators: 'human health' and 'ecosystem quality'. The dimension societal dimension comprises the indicators: 'risk of child labour', 'control of corruption' and 'freedom of speech'. All three dimensions aggregate the impacts differently: the ecological impacts are aggregated by their end-points, the social impacts by the maximum principle, which means the indicator with the lowest result dominates the overall result; and the economic criteria were selected and weighted by means of the analytical hierarchy process (AHP) with expert inputs. The AHP enables a structured decision-making (Vidal, Marle and Bocquet, 2011). This approach was developed with expert consultation and chemical analysis of different electronic products. The approach is comprehensive – it uses 29 different indicators - and it has been tested through aggregating the final results linearly or exponentially (Tuma *et al.,* 2014). However, its limitations include a lack of transparency, because the results are presented as a single, aggregate value, and a lack of information regarding uncertainty.

MDA 8. Cumulated raw material effort VDI 4599. The association of German engineers (VDI) is currently developing a standard with experts. This standard quantifies the raw material, products or product groups by means of relative scarcity, respectively availability and environmental implication (Lahl, 2012). This standard is the result of aggregating the sum of provisioning a product or service of raw material use along the value chain with unit tonne per tonne. The benefit is its origin, the VDI, who have developed practically applicable standards for inter alia resource efficiency: VDI 4800 (Giegrich *et al.*, 2014) and energy efficiency: VDI 4600 (VDI, 2012). The limitations are its long development period, with an originally foreseen publication in 2012 (Neugebauer, 2013) still not available while writing this review.

MDA 9. Integrated sustainability assessment for production and supply of raw material and primary energy carriers. A very recent (indicator-based) approach has been developed by experts from the European Union. It comprises the following areas of concerns: environment, economy, society and technology, which base on specific 'sustainability concerns'. These 'sustainability concerns' base on 15 indicators. Many indicators base on established evaluations such as the life cycle assessment, metal criticality determination or social life cycle assessment. The benefits comprise, this assessment approach bases on a systematic review and using quantitative indicators. However, the limitation is that this assessment has been developed with a limited number of experts. It is also unclear how the indicators were selected and there is no application (Dewulf *et al.*, 2015).

MDA 10. SCARCE method: critical resource use of Germany. This is a criticality evaluation at a country level. The components include: economy regarding criticality, society, and environment. These components are underpinned by 25 indicators, which were equally weighted. The spatial level is on country level. The approach was developed in collaboration with stakeholders during the 'Essenz' project (Bach *et al.*, 2017). The advantages include detailed assessment and knowledge on different aspects of resource assessment and critical reflection on its limitations. The disadvantages include an influence of different aspects and reasoning is not always clear. For instance, abiotic resource depletion can be considered as an environmental impact under ReCiPe, however in this approach it is part of the economic component and not of the environment.

MDA 11. RESCHECK resource criticality evaluation of scarce metals for small and medium size companies. This approach aims to evaluate the criticality of scarce metals of small and medium-sized enterprises, and explicitly address environmental and social implications. The components include the supply risk, vulnerability to supply restrictions, environmental implications, social implications, which include in total 19 indicators. A weighting is not yet implemented. It was developed for small and medium size corporate level companies (Spörri *et al.*, 2017). This approach was developed based on other existing criticality evaluations (Duclos, Otto and Konitzer, 2010; Graedel *et al.*, 2012). The advantages include, being developed as an online tool and the first approach, which was developed exclusively for scarce metals. The disadvantages comprise, being currently based on (semi)-quantitative indicators as well as a limited number of applications currently.

MDA 12. GRI: Gri 307: Environmental Compliance, 2016, Gri 103: Management Approach, 2016, Gri 419: Socioeconomic Compliance, 2016. This is a uniform reporting system of 3 sustainability pillars, of which some definitions are considered for the UNFC classification (Elliott, 2015). The components comprise economy, society, and environment. These are described by a number of reporting requirements rather than indicators. The legal compliance has a significant importance. The weighting is not applicable. This approach is on the corporate level. It is developed by integrating many stakeholders (GRI, 2016a, 2016b, 2016c). The advantages include extensive application to many organisations. The disadvantages comprise not applying quantitative indicators, so a precise comparison is limited.

MDA 13. Resilience in metal supply chain. This is a dynamic approach for evaluating raw material availability along raw material supply chains that has been used to investigate the REE supply chain. Sprecher *et al.* (2015) have defined the resilience of the material supply chain as "*the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available*." Similar to the other aforementioned 'availability' evaluation approaches, with this approach, the dimensions 'supply risk' and 'vulnerability to supply dimensions' were investigated. Both overlap on the metal supply and demand (Sprecher *et al.*, 2015). They have defined their system on three clear conceptual boundaries: society, the production system and the Neodymium Iron Boron ($Nd_2Fe_{14}B$) permanent magnet supply chain. Thereby, they were able to replicate the interruption of the supply chain and the 2010 REE supply crisis. Consequently, they have identified that the stockpiling of permanent magnets by a Japanese company caused the price to increase 10 fold. To prevent future crises, the authors recommend that a mineral tax may be implemented globally. This research has been conducted on the basis of primary and secondary data as well as interviews. Based on their findings, the authors suggest that further research is needed to eventually establish indicators for describing resilience mechanisms. The benefits are the dynamic system evaluation. As a limitation, one single threshold cannot be drawn without understanding the model in detail.

2.3.3 Elements of approaches for evaluating the prerequisites for recovery: availability and accessibility

The review was undertaken according to Cronin, Ryan and Coughlan (2008). This review aims to identify the number and relevant type of components, sub-components / indicators, scorings and aggregations based on the 16 evaluative approaches that can be used to evaluate the raw material accessibility. The terms components, sub-components / indicators are clarified in Table 1.

The components comprise: (i) 'geological knowledge', (ii) 'eligibility', (iii) 'technology', (iv)' economy', (v) 'society' and (vi) 'environment'. These components are based on the five domains framework (Giurco and Cooper, 2012; Simoni, 2012; UNU, 2012) and the UNFC (United Nations, 2013).

The indicator identification for these components can be straightforward but also complex, since the components themselves can be complex, such as 'economy' or 'society', and there is a vast amount of indicators within the concept (Graedel and Reck, 2015). The strategy in dealing with the more complex components, were to treat them as distinct but interpenetrating and semi-permeable concepts, which overlap and mix with other components (adopted from Feiz and Ammenberg, 2017). To overcome this, a class of sub-components was included such as 'technology' to clearly differentiate between the technological phases of i) **knowledge of machine and infrastructure development** and ii) **use of machine and infrastructure**. Note that the framework development in Chapter 5 does not include the sub-components, as it focuses on the component level and initially selected indicators. In Chapter 6, in a second step, the sub-components were included and the applied indicators were refined based in a wider set of indicators and expert opinions. For readability in this research, the components are highlighted with quotation marks and the sub-components and indicators are bold.

The following review considers only the most frequently used and relevant sub-components / indicators are, since there are vast amounts of sub-components / indicators. The components and sub-components / indicators were reflected based on the criteria, listed in Table 4, to develop a methodological framework on country level for scarce metals. The scarce metals often involve little available data (Table 4).

Table 4: Criteria that emerged from the research need for critical reflection of components and sub-components / indicators

Evaluation level	Criteria	Reference underpinning the research potential
Component	Active using in the subjects mining deposits in the anthroposphere (MDA) and mining deposits in the geosphere (MDG)	(Winterstetter *et al.*, 2015)
	Enabling a comparison on system level	(Graedel and Reck, 2015)
	Existing situation of data availability	(Graedel and Reck, 2015)
Sub-component / indicator	Enabling a comparison of MDA and MDG	(Lederer, Laner and Fellner, 2014; Winterstetter *et al.*, 2015)
	Enabling a comparison on system level	(Graedel and Reck, 2015)
	Being useable with limited data availability	(Bedder, 2015)
	Enabling a differentiation between countries	(Graedel *et al.*, 2015; Bach *et al.*, 2017)

2.3.3.1 Geological knowledge

The component 'geological knowledge' is described with the key words geological deposits, raw material products and grade-tonnage (Simoni *et al.*, 2015). This understanding of 'geological knowledge' is included in 14 of 16 reviewed evaluation approaches, in one implicitly and in one not. For instance, 'geological knowledge' is used in UNFC (2010) and Mateus *et al.* (2017).

The term 'geological knowledge' is established and widely used in relation to MDG. For MDA this term is new; consequently, its use might lead to confusion. However, this term is now being used in the development of the 'Draft Specifications for the Application of UNFC to Anthropogenic Resources' (Heuss-Aßbichler *et al.*, 2017). This indicates over time 'geological knowledge' might become general knowledge for this subject field. There was general criticism on 'geological knowledge' and its underlying data availability. Firstly, there is little continuously publicly available data apart from the USGS. Secondly, there are continuously new geological discoveries. Consequently, the underlying data requires revisions from time to time. Nevertheless, 'geological knowledge' was recommended to be used for short-term evaluations (Graedel and Reck, 2015).

Four sub-components / indicators are reviewed. The **sub-components / indicators related to reserve / resource** were used 7 times. This includes the **sub-component quantity** with the **indicator annual mass flow**; the **sub-component quality** with the **indicator mass fraction**; and the **sub-component mine life** with the **indicator time**. These indicators provide basic information for any mining intention. **The sub-component / indicator by-product dependency** was used 6 times. The by-product dependency is a metal share, which is produced as a by-product out of the host metal (Tuma *et al.*, 2014; SNL Metals & Mining, 2015), such as rare earths (by-product) from iron (host metal).

The sub-components / indicators related to **reserve / resource (sub-components: quantity, quality and mine life)** provide a general statement on a system level for a deposit in a specified area. They enable a differentiation between MDA and MDG, and are determinable with little available data (Jaireth, Hoatson and Miezitis, 2014). This use has been criticized, as data sources are not often transparent and differ largely in quality of different metals (Graedel and Reck, 2015). Further, this information alone does not provide a complete picture of mine development, yet it is still fundamental information (Mateus *et al.*, 2017) in an early project development stage (Winterstetter *et al.*, 2016a), such as reconnaissance exploration on macro level (Table 2). The indicator **by-product dependency** is important to be understood, since a by-product has a much greater risk of supply disruption (BGS, 2015). However, it is not applicable for a system level understanding. Furthermore, it does not lead to distinguishing between countries, as it is mine specific. This indicator cannot differentiate between MDA and MDG; rather it provides information for the specific metal. However, it could potentially be used with little available data.

The component 'geological knowledge' seems to be gradually becoming more understood. This suggests it may be used in an evaluation for both MDA and MDG. This includes the sub-component **quantity** with the indicator **annual mass flow**, **quality** with the indicator **mass fraction** and **mine life** with the indicator **time**. These indicators show frequent use. Despite the critics, they provide a general statement on any mining intention. Consequently, these sub-components and indicators are further applied (Table 5). The indicator **by-product dependency** is not further applied.

2.3.3.2 Eligibility

This component's context is described by the key words: strategic waste management (Simoni *et al.*, 2015) and political situation (Arndt and Ganino, 2012). In the 16 reviewed approaches, 'eligibility' was included in 4 approaches, in 9 implicitly and in 3 not. For instance, 'eligibility' was implicitly included in the supply risk (NRC, 2008; EC, 2014, 2017a; Sprecher *et al.*, 2015).

'Eligibility' has not been used yet in both MDA and MDG; however, the state of being eligible is central for the accessibility to raw materials. Since this term is new, there might be a challenge in understanding. It seems that data is available, however, while quantifying, the data certainty has to be reflected carefully (Graedel *et al.*, 2012).

Three sub-components are reviewed. The sub-components / indicator **market concentration** was used six times. This indicator provides information on the dependency of one or several market players (Weber and Heinrich, 2012). The sub-component **regulatory requirement** by means of the indicator **World Governance Index: 'rule of law'** was used three times. This indicator is defined as: 'capturing perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence' (Kaufmann, Kraay and Mastruzzi, 2010). The sub-component **policy implementation** by means of the indicator **Policy Potential Index (PPI), i.e. policy perception** was used twice. It provides 'a report card to governments on how attractive their policies are from the point of view of an exploration manager' (Fraser Institute, 2016).

The sub-component / indicator **market concentration** is a quantitative indicator and widely used. It is used not only in these approaches but also in national and international competition authorities (Weber and Heinrich, 2012). **Market concentration** has been criticised that this metric works well for a number of countries but not for others, due to limited data availability (Graedel and Reck, 2015). However, it can be applied for both MDA and MDG and provides a system level result. **Market concentration** can be used with limited available data and differentiates between countries. The sub-component **regulatory requirement** can be associated with two indicators, **World Governance Index: 'rule of law'** and **operating license**. The World Governance Index: 'rule of law' by means of the quality of contract enforcement and property rights, addresses explicitly this understanding of 'eligibility'. It is widely applied, for instance in (Bach *et al.*, 2017; EC, 2017a). This indicator can be used for comparing MDA and MDG on system level, is applicable with limited data availability, and differentiate between countries. The **operating license** provides information on whether a company has officially received the permission for operation. This is central knowledge for investigating the local situation, at an early project development stage. However, this indicator has not been used in the studied evaluation. Regardless, this indicator can be applied on a system level for both MDA and MDG. This indicator should be determinable with limited data. Since the operating process technologies are fixed to a certain place, a differentiation between the countries becomes possible. The sub-component **policy implementation** with the indicator **policy perception** could include **Policy Potential Index (PPI)** based on the well-known Fraser institute. As this indicator focuses on exploration managers, the country specific data is mainly from countries from MDG. Consequently, the PPI excludes most countries for MDA. Nevertheless, it is one of the few indicators that exclusively considers the mining industry. Further, it can be used for both MDA and MDG, is applicable on a system level and is used with limited available data.

The component 'eligibility' is new but seems central for MDG and MDA. This suggests, it may be used in evaluations for both MDA and MDG. This includes the sub-component **market concentration** with the indicator **market concentration**; sub-component **regulatory requirement** with the indicators **WGI 'rule of law'**, and **operating license**; and the sub-component **policy implementation** with the indicator **policy perception**. These indicators show a frequent use and meet all criteria. They were applied further as shown in Table 5.

2.3.3.3 Technology

This component's context is described by the key words mining production process, and recycling technology challenges (Simoni *et al.*, 2015). In the 16 reviewed approaches 'technology' was included 8 times, 7 times implicitly and once not. For instance, technology was used among substitution (NRC, 2008; Oakdene Hollins, 2008; Graedel *et al.*, 2012; Tuma *et al.*, 2014; BGS, 2015; Dewulf *et al.*, 2015; Sprecher *et al.*, 2015; Bach *et al.*, 2017). 'Technology' is central and actively used in both MDA and MDG. It is important to be understood on system-level, as it is central for a long-term supply of raw materials (Tilton, 2002). Its importance can be underpinned further. For instance, with technological innovation, the accessibility to a certain material can dramatically increase. Additionally, with a lack of alternative technologies, the accessibility to a certain material is not possible (Dewulf *et al.*, 2015). However, it becomes more central for detailed technical feasibility studies, since technologies can have a high influence on cost (Winterstetter *et al.*, 2016a). The data availability on 'technology' varies strongly depending on the applied indicators.

Two sub-components and five indicators were reviewed. The **sub-components** were split to first evaluate the status of '**knowledge of machine and infrastructure**' and second '**use of machine and infrastructure**'. The first sub-component is suggested for an early project development stage evaluation, since, at this stage, the technology is not always developed. Since the first sub-component is new, there was no use in the reviewed literature. For the second sub-component '**use of machine**

and infrastructure' five indicators were reviewed. The **recycling rate** was used five times, which provides a statement on the status of a technology and is commonly applied in the waste management sector (Schluep *et al.*, 2010). The **cumulative energy demand** was used once, which gives information on the energy consumption of a certain technology. The **global innovation index** was used once, which consists of 60 variables that are categorized under seven main components: institutions, infrastructure, human capacity, market sophistication, business sophistication, scientific output and creative outputs and well-being (Graedel *et al.*, 2012). The **exergy replacement costs** was used once, which is based on the exactly quantifiable law of thermodynamics (Nuss, 2016). It is defined as the energy required by the best available technology to produce from an EoL product/ rock, a metal to a reference state. Here the reference state is the starting point, i.e. EoL product/ rock. Measured by information on compound and chemical concentration (Valero *et al.*, 2014). The **substitutability** implicitly includes 'technology' and was used 11 times. The substitutability provides information on the technical ease of replacing a material in a product by another material with a similar function (Graedel *et al.*, 2012).

The sub-component / indicator, '**knowledge of machine and infrastructure'** can be quantified nominally with whether knowledge does not exist (0 points), is in research (1 points), scale up-phase (2 points), or large scale production (3 points). This indicator addresses all criteria as seen in Table 4. The differentiation on country level can be distinguished, depending on the country of operation. This indicator is important for an early-project stage evaluation, since technology has not always been developed. The sub-component '**use of machine and infrastructure**', includes the indicator **recycling rate**, which is widely used and defined in European legislations such as EU (2012). This rate is quantifiable and supports the differentiation between technologies. The recycling rate fits all criteria, as seen in Table 4, but the comparability between MDA and MDG. Since the recycling rate provides states information of the recycling system; this indicator's result could be expanded by determining the rate of a process, i.e. mining and processing. This named as **indexed annual rate of collection, mining recovery and processing recovery**. However, the recycling rate, which includes the collection rate, has recently been criticised that not all publicly available data is actually correct. For example, in Switzerland the official collection rates for paper and cardboard are 97%, but the actually estimated collection rate collection rate is 74% for paper and 89% for cardboard (Haupt, Vadenbo and Hellweg, 2017). The **cumulative energy demand** is commonly used in Life Cycle Assessments of raw materials, such as Simoni *et al.* (2015); and Wolfensberger *et al.* (2015). It fits all criteria as seen in Table 4. The differentiation of countries depends on the country in which energy is consumed. Moreover, this indicator was found to produce reliable results for investigating metals (Nuss and Eckelman, 2014). The **exergy replacement costs** fit all criteria for sub-components and indicators (Table 4). The differentiation of countries depends on the operating location. However, this indicator is very new and subsequently the data sources might be limited, as it was introduced for resource depletion in 2014 (Valero and Valero, 2014; Valero *et al.*, 2014). The **global innovation index** is well-reputed (INSEAD, 2015). It meets all indicator criteria as shown in Table 4. In particular, this indicator addresses the criteria 'enabling a differentiation between countries'. Nevertheless, the overall statement of only this indicator is limited. For instance Graedel *et al.,* (2012) used this indicator together with 'net import reliance' for describing susceptibility, which only implicitly includes 'technology'. The **substitutability** based on information in literature, which is often ranked qualitatively (Oakdene Hollins, 2008; Graedel *et al.*, 2012; BGS, 2015). It can be applied for both MDA and MDG and is on a system level. However, this indicator can be difficult to quantify correctly, due to limited data availability and quantitative determination (BGS, 2015). It is not possible to differentiate between countries. Moreover, this indicator has a limited overall statement on technology, as it provides a statement on the metals replacement potential (BGS, 2015).

The component 'technology', is understood and important. The sub-component and indicator **knowledge on machine and infrastructure** was further applied. For the sub-component **use of machine and infrastructure**, the indicators **indexed annual rate of collection, mining recovery and processing recovery**, the **cumulative energy demand** and **exergy replacement costs**, demonstrate high number of uses and meet all criteria. Consequently, they were further applied, as shown in Table 5. The indicator **global innovation index** and **substitutability** are not further investigated.

2.3.3.4 Economy

This component's context is described by the key words: costs of production facilities, REO, prices, value in REE stocks (Simoni *et al.*, 2015). In the 16 reviewed approaches, 'technology' was included in 12 evaluation approaches, in 2 implicitly and in 2 not. The use of 'economy' varies quite a lot. For instance 'economy' is often included in supply risk (NRC, 2008; EC, 2017a) or vulnerability to supply restriction (Graedel *et al.*, 2012). However, 'economy' as such was not quantified in the reviewed approaches.

'Economy' is a central aspect but difficult for various reasons. It is actively used in both MDA and MDG. The use of 'economy' is suggested for well-defined situations (Dewulf *et al.*, 2016), such as at the corporate level. However, it is less recommended for a more general setting that is less defined. Nevertheless, it is prevailing information especially for evaluations with a short-term availability consideration (Graedel and Reck, 2015). There might be lack of empirical data, while quantifying the domestic material consumption (Duclos, Otto and Konitzer, 2010). 'Economy' quantification can lack consistency over different elements. For example in the EC (2014), the material consumption of 'megasectors’ was not applicable for every investigated element (Graedel and Reck, 2015). However, the component ‘economy’ is important for any project-status.

Four sub-components / indicators were reviewed. The sub-component / indicator ‘**cost for collecting, mining and processing**’ was used 5 times. Costs include the expenses of collecting, mining and processing. The sub-component / indicator ‘**cost volatility for collection, mining and processing**’ was used twice. It provides information on the volatility of the raw material market. The cost volatility comprises the costs with the addition of dividing the costs year by year from a prior period. The sub-component / indicator **material consumption** was used three times, which is a monetary value for the use of material (NRC, 2008). The sub-component / indicator **material price** was used four times. This includes the material value (Sprecher *et al.*, 2015).

The **cost for collecting, mining and processing’** can be quantified by means of **operating costs of collecting, mining and processing**. This indicator can be applied to both MDA and MDG. This indicator was used to quantify the production costs of copper mining (Rosenau-Tornow *et al.*, 2009). However, this indicator lacks determination at both a country specific level and on a system level. Further, it cannot be applied for case studies with little available data. It was applied on a process level such as with landfill mining (Winterstetter *et al.*, 2015). Since the ‘operating costs of collecting, mining and processing’ were not applicable for this research, a different indicator was developed. Exchanges with an economist on a simple quantification resulted in the indicator **indexed costs in a country** (University of Southampton, 2017). This includes the product of human labour costs, production costs and material prices during collecting, mining processing. This new indicator has the advantage that it builds on an existing indicator regarding production costs (Rosenau-Tornow *et al.*, 2009), is applicable with little available data, and can be used for determinations on a system level. It further enables a clear differentiation between countries and enables comparability between mining MDA and MDG. However, it is limited by providing only information for an early-project statement, which in turn meets exactly the aim of this research. The uncertainty of the underlying data has to be considered carefully (Graedel and Reck, 2015). The subsequent sub-component **cost volatility for collecting, mining and processing** could include the indicator **indexed cost volatility in a country**. This has been little used. Nevertheless, it was successfully applied in MDG (Spörri *et al.*, 2017) and suggested in Dewulf *et al.* (2015). It provides information on supply security (Dewulf *et al.*, 2015). It can be justified and criticized as the **indexed costs in a country**. Additionally, the indexed cost volatility depends much on the considered years of comparison and can vary quite a lot between the selected years. This demonstrated the fluctuating market situation of rare earth (Sprecher *et al.*, 2015). The indicator **material consumption** and **material price** provides a less generic statement on the economic situation than the costs. Both indicators would enable a comparison between MDA and MDG and also enable a comparison on a system level. ‘Material consumption’ is difficult to quantify. Furthermore this indicator is problematic to justify, because of lack of data and being clearly specifiable (Graedel and Reck, 2015). Similarly, the material price is not country specific. Neither meets the requirements of the identified criteria as seen in Table 4.

The component ‘economy’ is understood and important. The following sub-components and indicators were frequently used and meet all criteria. This includes the sub-components **costs for collecting, mining and processing** with the indicator **indexed costs in a country**; and the subcomponent **cost volatility for collecting, mining and processing** with the indicator **indexed costs in a country**. Consequently they were applied further as seen in Table 5. The indicators **material consumption** and **material price** were not investigated further.

2.3.3.5 Society

This component’s context is described by the key words social norms and obligations (UNU, 2012), and social issues (Simoni *et al.*, 2015). In the 16 reviewed approaches, society was included in 10 evaluation approaches, in 1 implicitly and in 5 not. For instance, it was included in the World Governance Index as part of supply risk (EC, 2014).

‘Society’ is considered as very important to address the issues of sustainability (Graedel and Reck, 2015) which must be addressed from the beginning of an evaluation (Corder, McLellan and Green, 2010). This component is actively used in both MDA and MDG. Further, the societal indicators are rapidly growing, in particular human right compliance (Merry, 2011). This component is on a system level. Many indicators exist, however the comparability can be challenging, as comparing between different countries is not always easy (ILO, 2016).

Four sub-components and six indicators were reviewed. The sub-components were selected for understanding both the local and national social situations by means of **social regulatory requirements**, **working conditions**, **human rights implications**, and **societal stability**. For **social regulatory requirements**, this new indicator was suggested for determining the use of **social regulations and standards**, such as the OHSAS18001:2007. As this indicator is new, it cannot be reviewed. The **sub-component working condition** could be quantified by the indicators **(non-fatal) occupational injuries** and **(excessive) working hours**, they aim to describe local and social mining issues. These indicators were used once. To understand the national social situation, **the sub-component ‘human rights implications’** can be quantified by means of **World Governance Index: ‘Voice and Accountability’**, which was used four times. This indicator is described as ‘capturing perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media' (Kaufmann, Kraay and Mastruzzi, 2010). This indicator was also called **freedom of speech** (Tuma *et al.*, 2014), which name is suggested for this research. The sub-component **societal stability**, can be quantified by means of the indicator **World Governance Index: 'Political Stability and Absence of Violence/Terrorism'**, which was used six times. This indicator is suggested to be called **political stability**, to ensure a linkage of the used sub-component and indicator names. 'Social stability' can be quantified by the indicator the **World Governance Index: 'Control of corruption'**, which was used three times. This indicator is suggested to be called **corruption perception** to ensure a linkage of the used sub-component and indicator names. The 'Political Stability and Absence of Violence/Terrorism' is described as 'capturing perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically-motivated violence and terrorism' and the control of corruption described as 'Capturing perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as 'capture' of the state by elites and private interests' (Kaufmann, Kraay and Mastruzzi, 2010).

The sub-component / indicator **social regulations and standards** is suggested as central for determining the social impacts from mining, which can be quantified with either the existence or absence of publically available standards. This indicator meets all criteria for this evaluation as seen in Table 4. In particular, it resorts to internationally recognised guidelines, which consider all basic social needs. Consequently, this indicator sums up many central aspects in one measure. However in practise, information on the OHSAS standards are not always easy to retrieve online. The sub-component **working conditions**' indicators **(non-fatal) occupational injuries** and **(excessive) working hours** are used in social life cycle assessment (Dewulf *et al.,* 2015). They meet all criteria for indicators as seen in Table 4. In particular, they can be used for information regarding local mining issues, which information is also valuable on system level. These indicators are quantified on country level (ILO, 2017). To understand the national social situation, the sub-components **human rights implications and societal stability** are critically reflected upon together as both originate from the World Governance Indexes (WGI). These indexes are widely used (Graedel *et al.*, 2012; Spiers, Houari and Gross, 2013; EC, 2017a). The WGI are well established and are based on solid research, are quantitative and on country level (Rohwer, 2009). They further enable a comparison between MDA and MDG.

The component 'society', is understood and important. The following sub-components and indicators are used in the reviewed approaches and meet all desired criteria. They include the sub-component / indicator **social regulatory requirement**; the sub-component **working condition** with the indicators **non-fatal occupational injuries** and **working hours**; the sub-component **human rights implications** with the indicator **freedom of speech** and the sub-component **societal stability** with the indicators **political stability** and **corruption perception**. Consequently, they were applied further, as seen in Table 5.

2.3.3.6 Environment

This component's context is described by the key words: ecotoxic effects, environmental impact of production (Simoni *et al.*, 2015) and human health (Graedel *et al.*, 2012). In the 16 reviewed approaches, 'environment' was included in 12 evaluation approaches, in 2 implicitly and in 2 not. For instance, 'environment' was included in environmental implications (Graedel *et al.*, 2012; Dewulf *et al.*, 2015; Bach *et al.*, 2017; Mateus *et al.*, 2017). 'Environment' is actively used in both MDA and MDG and considered as very important to address the issues of sustainability (Graedel and Reck, 2015). In particular it is central to address the 'environment' from an early project development stage (Corder, McLellan and Green, 2010). 'Environment' can be used on the system level.

Two sub-components and four indicators were considered. The sub-component was selected for understanding both the local and national environmental situation by means of **environmental regulatory requirements** and **total environmental impacts**. For understanding the environmental regulatory requirements, a new indicator is proposed, namely **environmental regulations and standards**, such as ISO 14001 guidelines. This enables an understanding of the local and environmental situation. To investigate the current total impact to the environment, it was proposed to use the sub-component **total environmental impacts** by means of a Life Cycle Analysis with the method ReCiPe. ReCiPe was used four times. The ReCiPe includes the cumulative indicators ecosystems, resource depletion and human health (Goedkoop *et al.*, 2013). Often resource depletion is included, however since the resource depletion is part of other aspects such as physical availability (Bach *et al.*, 2017), it could be excluded for determining the **total environmental impacts**.

The sub-component **environmental regulations requirement** with the indicator '**environmental regulations and standards**' was suggested, since for an early project development stage evaluation it is central to understand the present situation of a mining company. This indicator meets all criteria for this research as seen in Table 4. In particular, it resorts to internationally recognised guidelines, which include environmental legislation. The subcomponent **total environmental impacts** by means of ReCiPe is well known for Life Cycle Analysis. ReCiPe builds on the methods Eco-indicator 99 and CML Handbook on LCA (2002) (Goedkoop *et al.*, 2013). Moreoever, ReCiPe gives a good representation on the environmental impacts, since many impact categories are included (Papadimitriou, 2016) and ReCiPe is considered as the most robust end-point method (Sonnemann *et al.*, 2015). This indicator meets all criteria as seen in Table 4. In particular, it is based on a method that was continuously developed over several years and has now become mainstream. However, there remain challenges such as allocating the share of environmental impact, different units in one comparable system and uncertainty analysis (Finkbeiner *et al.*, 2014). This method has be criticized for not capturing synergetic effects of e.g. joint supply chain (Moeller, 2015). However, this method enables a systematic way to evaluate complex environmental issues (Tillman and Baumann, 2004), which can be on varied spatial levels such as local, national and global levels (Brunner and Rechberger, 2004).

The component 'environment' is understood and important. The following sub-components and indicators are used in the reviewed approaches and meet all desired criteria. They include the sub-component **environmental regulations requirement** with the indicator **environmental regulations and standards**; and the **total environmental impacts** with the indicators **ecosystems**, **resource depletion** and **human health**. Consequently, they were applied further as seen in Table 5.

2.3.3.7 Scoring and its weighting

The reflection in this section aims at identifying a scoring approach that provides justice to an early-project stage evaluation with limited available data. Overall, this review did show there were various types of scoring and weighting. Generally, it is difficult to justify the scoring (Bach *et al.*, 2017). Many ranked from 1 to 3 (Oakdene Hollins, 2008; BGS, 2015), 1 to 3 or 4 (UNFC, 2010), 1 to 100 (Graedel *et al.*, 2012), and 1 to 5 (Moss *et al.*, 2013; Wolfensberger *et al.*, 2015; Bach *et al.*, 2017). Other evaluation approaches used indicators with unequal scoring based on expert workshops and surveys (Tuma *et al.*, 2014); or based on the component importance (Mateus *et al.*, 2017). The impacts on society can be ranked according to the maximum principle (Tuma *et al.*, 2014). The impact on the environment can be ranked based on the end-point values (Tuma *et al.*, 2014), (Graedel *et al.*, 2012). Regarding scoring method development, apart from Tuma *et al.* (2014), there is little information available on the scoring method development. Regardless of these difficulties, a scoring aids to provide an indication on the global raw material situation. Consequently, a widely used scoring approach (Oakdene Hollins, 2008; BGS, 2015), that does justice to the little available data and associated high data uncertainty, was selected: 1 to 3 with higher, moderate and lower accessibility.

2.3.3.8 Aggregation and its weighting

The reflection in this section aims at identifying the most transparent aggregation approach, since the intended evaluation highlights hotspots for in-depth analysis and provides basic knowledge for other more-detailed evaluations and classifications. For this, different aggregation methods were identified as listed in a) to g): a) the highest supply risk indicator can result in the final score (NRC, 2008); b) the supply restrictions can be multiplied (NRC, 2008); c) the indicators can be summed (EC, 2014, 2017a) (Bach *et al.*, 2017); d) the aggregation can result in a final score that includes different weighting (Mateus *et al.*, 2017); e) the aggregation can result in three distinctive axis (UNFC, 2010; Graedel *et al.*, 2012); f) the indicators were not aggregated (Oakdene Hollins, 2008); g) the aggregated result can be company or product specific, rather than country specific (Tuma *et al.*, 2014). This diversity showed that the aggregation methods vary greatly. While aggregating, the overall results of each indicator can be aggregated to an easily understandable result. However, the knowledge of the underlying indicators is no longer transparent. Moreover, every aggregation of indicators includes a weighting, remains subjective and adds limited additional value to the interpretation of the results (Bach *et al.*, 2017). There can be much confusion in an arbitrarily selected threshold, for instance in separating 'critical raw materials' from 'non-critical raw materials' (Graedel and Reck, 2015). Consequently, for this evaluation, the most transparent aggregation was implemented, i.e. representing each indicator result separately and aggregate only to maximum one level higher. This in turn can directly be used in other evaluation approaches such as UNFC (UNFC, 2010, 2016).

Table 5: Narrowing the research scope of identifying the sub-components and indicators for framework development. For Chapter 5, the framework development did not include the sub-component level. Much more it aimed to provide an initial framework and application with the use of the most frequent indicators and quantifiable indicators, despite the limited data availability. For Chapter 6, all identified sub-components and indicators were reflected, confirmed, consolidated, and applied.

Component	No. of uses	Sub-component	Indicator	No. of uses	Used in Chapter 5: frame-work evelop-ment	Used in Chapter 6: Re-finement and con-firmation
Geological knowledge	14	Quantity	Annual mass flow	7	✓	✓
		Quality	Mass fraction		✓	✓
		Mine life	Time	0		✓
Eligibility	4	Market concentration	Market concentration	6		✓
		Regulatory requirement	WGI 'rule of law'	3	✓	✓
			Operating license	0		✓
		Policy implementation	Policy perception	2		✓
Technology	8	Knowledge of machine and infrastructure	Knowledge of machine and infrastructure	0		✓
		Use of machine and infrastructure	Indexed annual rate of collection, mining recovery and processing recovery	5	✓ (simplified with recovery rate of a technology)	✓
			Cumulative energy demand	1		✓
			Exergy replacement costs	1		✓
Economy	12	Costs for collecting, mining and processing	Indexed costs in a country	5	✓ (simplified with value of raw material)	✓
		Cost volatility for collecting, mining and processing	Indexed cost volatility in a country	2		✓
Society	10	Social regulatory requirement	Social regulations and standards	0		✓
		Working conditions	Working hours	0		✓
			Non-fatal occupational injuries	1		✓
		Human rights implications	Freedom of speech	4		✓
		Societal stability	Political stability	6	✓	✓
			Corruption perception	3		✓
Environment	10	Environmental regulatory requirement	Environmental regulations and standards	0		✓
		Total environmental impacts	Ecosystems	4	✓ (simplified with CO_2 equivalent)	✓
			Resource depletion	0		✓
			Human health	4		✓

2.3.4 Implications and potential limitations for evaluating the prerequisites of recovery: availability and accessibility

'Availability', which is in addition to 'accessibility', a prerequisite for the recovery of raw materials, is commonly used in relation to raw material classifications. However, it has been pointed out that this term should be expanded by 'accessibility', which explicitly includes how to get to the material by considering the depth and accounting for the raw material depletion (USDOE, 1996). Since the material consumption will increase in the long-term, it is crucial to understand the accessibility to raw materials in addition to 'availability'. While understanding the latter alone, it is more likely that resource shortages will occur (Rankin, 2011).

The current approaches for evaluating the availability of raw materials integrate comprehensive assessments with many components and indicators. They are based on rigorous primary and secondary data as well as expert consultations, by integrating the systematic analytical hierarchy process (Tuma *et al.*, 2014). This, together with currently not employing a fixed set of indicators, means that the results should be considered as a promising innovative application that requires further research (Velis and Brunner, 2013).

To understand the raw material situation, it is central to consider the interaction of different components, which originate from the five domain framework (Giurco and Cooper, 2012). These components range from 'economy', 'society', 'environment 'and 'governance', respective to 'eligibility' (adopted from Simoni *et al.,* 2015), which have been expanded with 'geological knowledge' (Mateus *et al.*, 2017). These different components are in turn important for ensuring a comprehensive understanding of sustainability implications (Cooper and Giurco, 2011; Gleich *et al.*, 2013; Mateus *et al.*, 2017). For details on the different components, see section 2.3.3. These efforts represent positive steps in enhancing the understanding of, and providing a novel solution to raw materials issues. The five domain framework has clearly influenced raw material understanding in a broader system level context, such as resource strategy of a region in Switzerland (Simoni *et al.*, 2015).

These six components, which build the joint fundamentals, were suggested with the purpose of developing a more comprehensive evaluation of raw materials for governments and industries, so that eventually the current raw material management could be advanced with a novel perspective. Such a novel perspective should include the current situation but also highlight potential for improvements along the supply chain and waste management. In this way, this evaluation will move toward providing a basis not only for availability but also for the accessibility of raw materials in the context of an early project development stage statement under sustainability considerations.

The limitations of advancing the ‘availability’ to the ‘accessibility’ evaluation approach include (i) embedding a new term and its concept and (ii) developing an approach with often hidden expert knowledge. As a consequence of these limitations, an additional challenge is the usefulness demonstration of any advanced evaluation approach. Further, with little existing input data (Graedel *et al.*, 2012), the uncertainty increases. In this way, the evaluation becomes even more subject to the condition of the case specific abstraction and will always be incomplete. Therefore, it is required to be transparent about its limitations as similar with a semi-quantitative uncertainty scoring as applied by Mateus *et al.* (2017). Definite conclusions about the relative material accessibility cannot be made, as this approach fails to account for a number of potential influences on understanding accessibility and availability of raw materials, such as dynamic modelling, aggregation of the results and being on detailed level of investigation. Additionally, on a more theoretical level, the availability and accessibility evaluation address a situation with complex multifaceted interactions of any problem, a so-called ‘wicked’ problem. This means, on a theoretical level, there is no true or false outcome and there is no ultimate test to a solution (Cooper and Giurco, 2011; Townend, 2015), as these problems remain open-ended and inconclusive (Feiz and Ammenberg, 2017). This, together with the limitations imposed by embedding a new term, means that the result should only be considered as indicative.

Therefore, the concluding statement might be limited in its depth but a more accurate and broad applicable evaluation for a specific case study. Ultimately, it then becomes central to communicate the specific focus clearly.

2.3.5 Gap in scientific knowledge for evaluating the prerequisites of recovery: availability and accessibility

While existing approaches that seek to evaluate availability and accessibility of a raw material serve a purpose, they are not fully suitable as a basis for policy recommendations. Rather, they should serve as a first step in the identification of MDA and MDG that suggest future analysis. To effectively understand the accessibility of raw materials, it is essential to initially and systematically explore the opportunities and the use of a new term to develop a methodological framework: accessibility evaluation for MDA and MDG under sustainability considerations. This should be applied firstly to demonstrate the utility of this framework. Then the accessibility evaluation should be refined, confirmed, consolidated and applied. As a consequence, this would provide a more suitable evidence base of advancing industrial policy and providing a greater indication on today’s raw material issues for MDA and MDG.

To achieve this - and with this advance the availability evaluation approaches - it is central that the ‘accessibility’ to raw materials explicitly accounts for the raw material depletion (USDOE, 1996). This remains a priority today, as raw material management requires rethinking (Ongondo, Williams and Whitlock, 2015). The use of linguistic approaches and anonymous collaboration with experts and practical applications are central for a method development and should be a priority. This then allows the development of a more robust interdisciplinary methodological framework that includes sustainability considerations but also technological, economic and regulatory components to quantitatively evaluate the accessibility of raw materials (adopted from Velis and Brunner, 2013; Hagelüken, 2014).

Chapter 3 Research methodologies

3.1 Linkage of chapter to PhD research

This chapter provides a reflection of the different methods applied in this research. Each section is dedicated to the discussion of the methodologies underlying the main Chapters 4, 5, and 6. The methodologies are presented here in their order of appearance in Chapters 4, 5, and 6.

3.2 Methodology for Chapter 4

3.2.1 Group techniques for framework development and identification of analogies

To develop the geological reconnaissance, it was necessary to consult experts. To identify the best suited method, group techniques were first described and then reflected. Table 6 provides a comparison on how to overcome difficulties of the focus group, nominal group technique, and Delphi technique.

3.2.1.1 Focus group (FG)

A series of direct interactions within a group, i.e. focus group, include carefully planned discussions or interviews. These interactions are designed to obtain information from a group of experts of a defined area of interest at the same temporal and spatial location. A moderator usually leads the interactions (Landeta, Barrutia and Lertxundi, 2011). Focus groups are advantageous as participants often report feelings of social satisfaction such as power, status, and recognition making participants likely to share valuable information. The FG is flexible and has high subject validity. The experts can learn from each other though the sharing of information and opinions. This method is very useful in the creative process of generating and ordering ideas (Landeta, Barrutia and Lertxundi, 2011). It is also useful to intensely debate specific topics (Spickermann, Grienitz and von der Gracht, 2014). Conversely the disadvantages include the possibility of participants conforming to group opinion for various reasons such as haste, group thinking, desire to be accepted by the group, distraction of certain personalities, and personal problems (Landeta, Barrutia and Lertxundi, 2011).

3.2.1.2 Nominal Group Technique (NGT)

This technique is a semi quantitative and qualitative approach. It involves discussions within focus group but also parts which are structured and independent from the group as well (Lennon, Glasper, Alan and Capenter, Diane, 2012). The NGT process is explained as follows. First the study leader presents the question. Next, the experts answer on a paper silently. The experts are then presenting their own ideas without comments to the group and then make an assessment and an anonymous ranking. Finally, the study manager integrates the outcome of each expert and leads a discussion (Landeta, Barrutia and Lertxundi, 2011). The advantages are much the same as for the focus group as seen in section 3.2.1.1. The individual response section makes it possible to overcome the disadvantages of the focus group, such as the possibility of group conformance. However, this leaves less space for discussion, limited participation number and one question for one NGT process (Lennon, Glasper, Alan and Capenter, Diane, 2012).

3.2.1.3 Delphi technique

The Delphi technique is a structured and iterative approach for distilling an anonymous consensus, typically through a multi-round survey with a panel of experts independent from each other. (Paré *et al.*, 2013). After the first survey, the experts are presented the aggregate group answers from the previous round in order to facilitate consensus establishment. Among the advantages of this technique are its flexibility in time and space, its structured approach and independent responds (Walters and Javernick-Will, 2015). Its disadvantages include limited creativity, emotional inclusion of participants, and correctness of responding the questions (Landeta, Barrutia and Lertxundi, 2011).

3.2.1.4 Selection of methods

The FG was selected to meet the requirements for a structured brainstorming process (see 3.4.1.1) for the framework development, as this method enables the creative potential of each expert. For the identification of analogies, the Delphi technique was selected to meet the requirements, as the participating experts would have limited influence over each other.

Table 6: Likelihood of overcoming difficulties among focused group, nominal group, and Delphi technique (Landeta, Barrutia and Lertxundi, 2011).

Difficulties	Capacity of the technique to overcome difficulties of configuration and work in groups of professional experts		
	Groups of direct interaction (FG)	**Nominal Groups (NGT)**	**Delphi technique**
Previous ignorance of the technique for consolation and interaction	High	Low	Low
Hard to make up a group with the right number of desired experts	Low	Low	High
Hard to coincide in time and space	Low	Low	High
Little availability of time	Medium	Medium	Medium
Need fopr relation and social recognition	High	Medium	Low

Difficulties	**Capacity of the technique to overcome difficulties of configuration and work in groups of professional experts**		
	Groups of direct interaction (FG)	**Nominal Groups (NGT)**	**Delphi technique**
Need for learning and improvement	Medium	Medium	Medium
Need for immediate feedback and perceived sense of closure	Low	High	Medium
Difficulties in adopting the viewpoint of the study and the investigator	High	Medium	Low
Tendency to devote little time to reflecting on the questions	Low	Medium	High
Risk of inhabitation due to dominant members or to other causes	Low	Medium	High
Risk of behaviours that seek social approvals	Low	Medium	High
Conformity pressure in decision –making	Low	High	Medium
Risk of distraction	Low	High	High
Difficulties in producing, contributing, and reflecting new ideas in presence of other group members	Low	High	Medium

3.2.1.5 Application of focus groups for framework development

To establish and confirm the relationship between geological and anthropogenic processes, four consecutive Delphi workshops were organised with four experts: two geologists and two resource management researchers from academia. The knowledge generation process commenced by critically analysing, identifying and discussing the processes of the geologic ore deposit formation, i.e. genetic ore deposit formation understanding and its resulting classification. On this basis, mining, processing and the material life-cycle processes were analysed, deconstructed and categorised. This was followed by the development of a commonly agreed overview framework. The initial framework was then independently synthesised and resynthesized. To verify the emerged framework the same experts were re-consulted (Jabareen, 2009).

3.2.2 Application of Delphi technique for identifying analogies

The analogies, i.e. similarities or correspondences between elements of the framework, were identified in a Delphi group workshop with the above mentioned experts from geology and resource management (Börjeson *et al.*, 2006). The questionnaire included a presentation, see section D.1, and the corresponding answer sheets for independent completion included prepared answer sheets, see section D.2. The analogy identified by the experts to be most relevant was further elaborated for the case of REE in WEEE, which required a specification both of the crust-surface geochemical cycle and of the product cycle.

3.2.3 Development of characterisation and evaluation approach for three REE EoL products

To determine the anthropogenic deposit characteristics, typical geological deposit characterisation approaches were identified and critically analysed through literature research. To confirm the selection of a meaningful geological deposit characterisation and evaluation, the same experts as within the framework development were consulted (Börjeson *et al.*, 2006).

This consultation led to a critical analysis of the 'geological setting' characterisation of geological deposits according to Hoatson, Jaireth and Miezitis (2011). Overall, this characterisation provides a continually narrowing and comprehensive understanding of a geological deposit with a focus on its associated minerals and different life-stages. Specifically, to enable this perspective the analysis was concluded with a selection of criteria that allow the characterisation of the 'geological setting'. These criteria encompass: the geographical 'location' of the deposit, the 'geological context' (instead of the repetitive criteria 'geological setting'), 'host rocks', 'REE mineralisation', the 'age of mineralisation', and 'current status' (Table 10). The criteria describing the 'source of REE' and 'genetic modelling' were not included. The former is redundant with the specific REE deposit selection and the latter provides a strong congruence with the criterion 'host rock'. The characterisation of the 'geological setting' concludes with the criterion 'current statuses'. Those criteria that passed this analysis were adopted for mining of the anthroposphere.

The selected criteria were first applied to an example geological REE deposit as described by Hoatson, Jaireth and Miezitis (2011) and then to three EoL products of anthropogenic deposits: i) Neodymium-Iron-Boron permanent magnet, ii) fluorescent lamp with phosphors containing Europium and iii) fibre optic cable doped with Erbium.

For the evaluation of the anthropogenic deposits, the UNFC classification (UNFC, 2010) was selected. This classification was critically analysed, and then the category 'geological knowledge' was chosen on common agreement between the four experts and the principal investigator (Jabareen, 2009).

3.3 Methodology for Chapter 5

Text Mining is a method which can be used to explore knowledge. This includes exploring the fundamental knowledge of 'accessibility'. This is part of answering research aim (ii).

In text mining, many approaches and applications have emerged. To overcome the many approaches, decision guidance's is required. A strategy in dealing with these many strategies has to stages: (i) to apply a decision guidance by a decision tree (Figure 5) and (ii) to confirm the result of the decision guidance by understanding text mining and its related fields (Seidel, 2013). The stage (i) with a decision tree resulted in the 'concept extraction', which addresses this study's research objective (ii) of building the fundamental knowledge of 'accessibility'.

To confirm the results of the decision guidance, three criteria were selected for identifying the text mining and their related fields: (i) text mining has to be in the centre; (ii) the approach has to base the investigation on a statistical method; and (iii) the approach should be analysing and synthesising the language and speech with computers (Oxford Dictionaries, 2018a). The resulting approach was 'concept extraction', which confirms the result of (i) the decision guidance by a decision tree. Consequently, the resulting approach 'concept extraction' was applied.

There are different concept extraction approaches. To identify the most fitting concept extraction approach, such approaches were described and discussed. Mala and Lobiyal (2015) first identify the essential characteristics by an algorithm. Second, they employ their expert knowledge to identify a concept. Finally, this concept is used as a model for computational extraction of the final concept. As a limitation, they do not use semantic methods. Gelfand, Wulfekuhler and Puch (1998) applied concept extraction on plain text. They identified relationships in words and texts to form conceptual groups. On this basis relationships between word senses were identified. As a limitation, statistical analysis was lacking. Durmuşoğlu (2016) applied concept extraction as a pre-assessment on past research topics from electronics. In their approach they combined similar documents to the same concept. Then they identified common concepts, which included statistical analysis. As a limitation, there was a lack of systematic semantic analysis. Weinhofer (2010) suggests an approach for extraction of semantic relevant data for any topic. This approach includes the steps: text preparation, text analysis (including structural, statistical and semantic analysis) and determination of relevant data and then extraction of concepts, since this approach includes both statistical and semantic analysis. This approach was applied in the research to answer the research aim (ii).

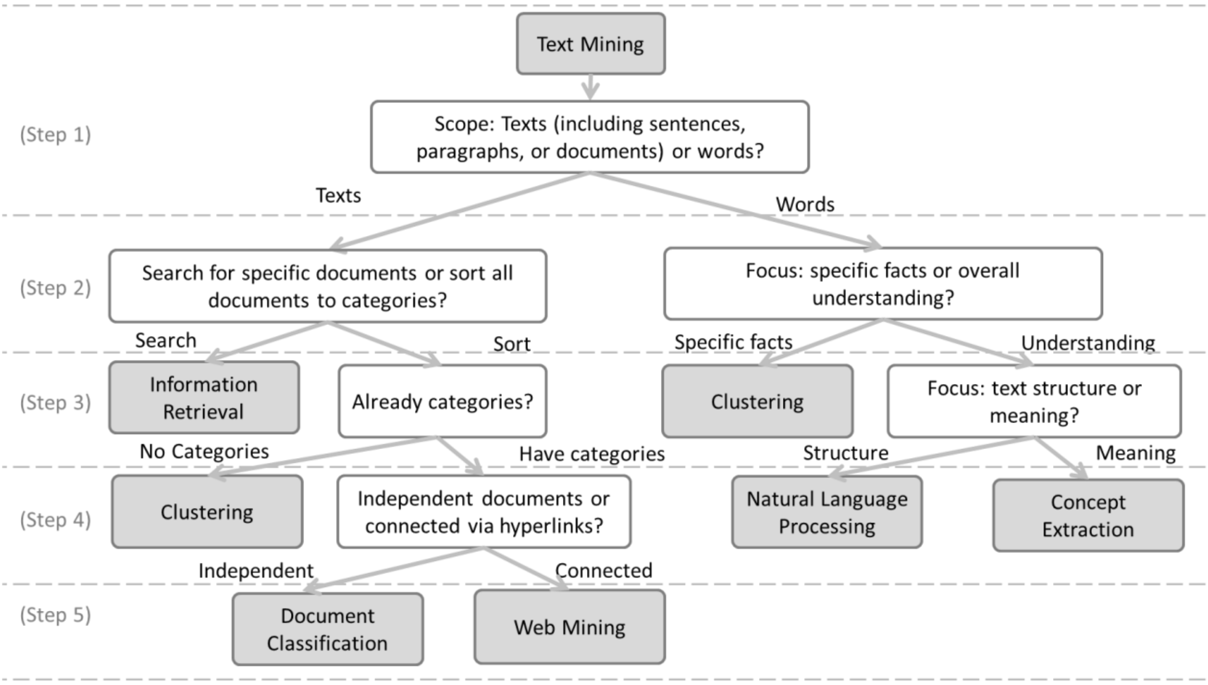

Figure 5: Decision tree in text mining to identify application area (adopted from Seidel, 2013).

3.3.1 Application of extraction of conceptual framework

Concept extraction was used to elucidate the meaning and use of accessibility and related terms. This process comprised four main stages: pre-processing, text analysis, establishment, and concept extraction (Figure 6), based on the work of Weinhofer (2010).

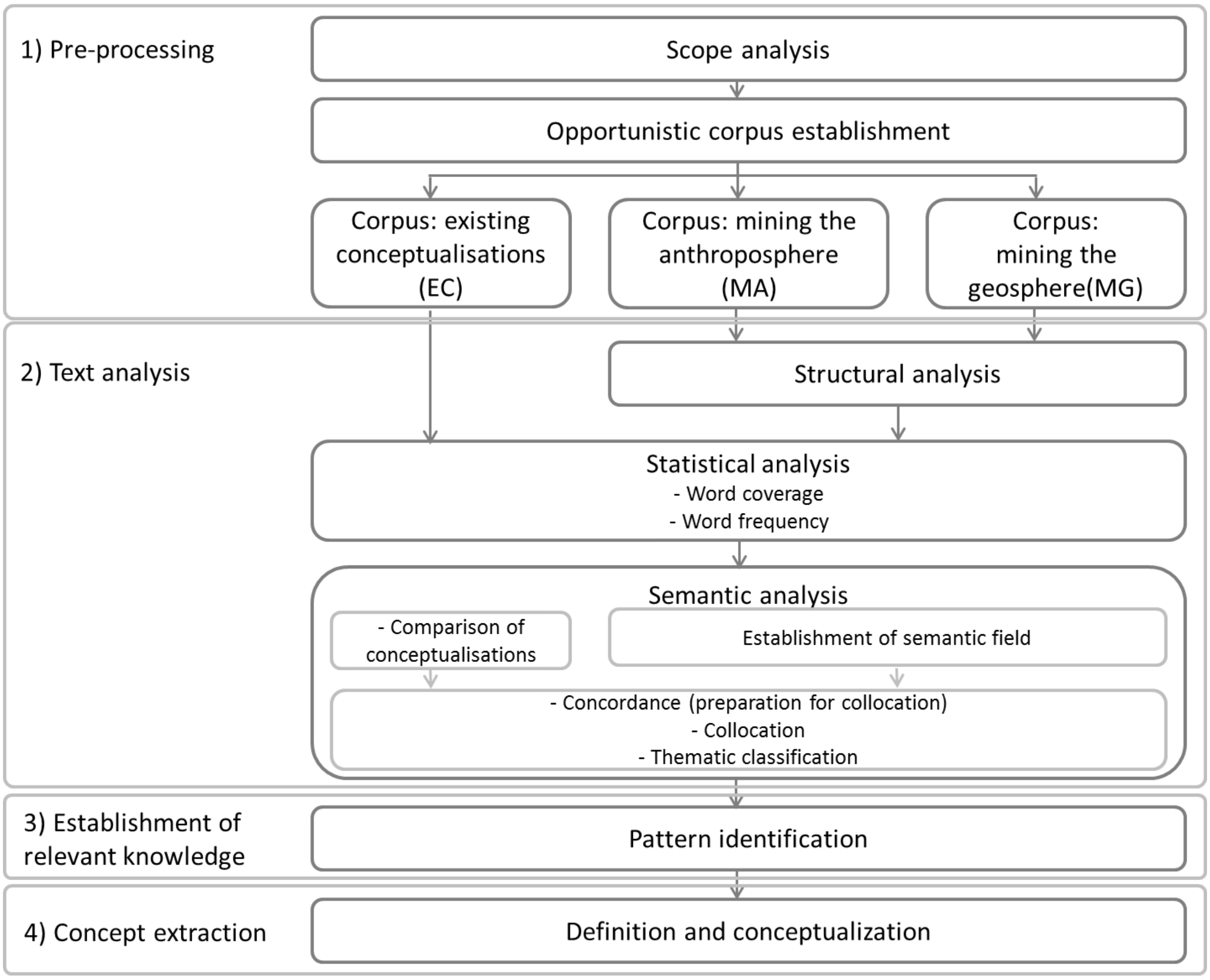

Figure 6: Sequential methodological approach: concept extraction for developing the conceptual framework for evaluating accessibility. Adopted from Weinhofer (2010).

3.3.1.1 Pre-processing

The scope of this research was determined and the opportunistic corpora[9] were established (Figure 1). For the former, a standard definition of 'accessibility' was created by critically reflecting the definitions and synsets[10] from the Cambridge (Cambridge Dictionaries Online, 2014), Oxford (Oxford Dictionaries, 2014), WordNet[11] (WordNet, 2014), and Britannica (Britannica Academic Dictionary, 2014) Dictionaries. Three opportunistic corpora were developed: 'existing conceptualisations' (EC), 'mining the anthroposphere' (MA), and 'mining the geosphere' (MG). The EC corpus was created for the pur-

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[9] 'Opportunistic corpus' is a selection of texts that are needed for the present purpose (Hausser, 2014). They often represents an incomplete collection of electronic texts (Sekhar, 2008).

[10] A set of synonyms (WordNet, 2014).

[11] 'WordNet' is at: large lexical database of English that covers a wide range of words, establishes cross linkages between them and is widely applied in linguistics. Nouns, verbs, adjectives and adverbs are grouped into sets of cognitive synonyms (synsets), each expressing a distinct concept (WordNet, 2014).

pose of analysing the use of ‘accessibility’ and its conceptualisation. For this, relevant literature sources were identified through a key word search for ‘concept of accessibility’ and ‘concept of availability’ in *Google Scholar*, *Scopus,* and *Google*. Thereafter, the MA and MG were built with the aim of investigating the use of ‘accessibility’ and its related terms. Both these corpora were developed based on the bibliography of Simoni (2012) as suggested by Cronin *et al.* (2008). This literature selection was expanded with a scholarly article search in *Scopus* using different combinations of the keywords ‘accessibility’, ‘integrated assessment’, ‘mineral resources’, ‘mineral reserves, ‘quantitative assessment’, and ‘environment’. The 275 documents consulted are shown in the Supporting infor-information, section F.1.

3.3.1.2 Text analysis

Stepwise analysis of the literature in the MA and MG corpora focused on three aspects: 1) structural; 2) statistical, and 3) semantic[12] analysis (Figure 6).

For the structural analysis, the content of the text headings in the literature were analysed. This step thereby obtained a general understanding of the relative usage of the term ‘accessibility’ and related terms in the two mining corpora (MA and MG). Text headings were analysed as they give a direct indication of the content of the main text body (Weinhofer, 2010).

For the statistical analysis, the coverage and distribution of the use of the words ‘accessibility’ and other related keywords were analysed. Word coverage identifies how often a term occurs and whether it is used in many different documents, whilst implying importance in meaning for a document. The word coverage is analysed following Zipf’s law (Li, 1992), which can be used to identify the phenomena whereby a few words occur often and the majority of words occur sparingly. For instance, the most frequent 150 words usually account for around half the words of a corpus (Powers, 1998). The distribution analysis quantifies terminological variance in sections of text and identifies the relative frequency of the most used terms (see Supporting information, section F.2, for details).

For the semantic analysis, I analysed (1) the meaning of conceptualisations, (2) semantic field creation, (3) collocation and (4) thematic classification. To identify a viable concept at the system level in the EC corpus literature, definitions of the word ‘accessibility’ were compared and contrasted. In parallel, a semantic field around ‘accessibility’ was established, which provided the basis for connecting this conceptualisation of accessibility with EoL products. A collocation analysis was then carried out on each of the three corpora. Collocation analysis is the most important and widely used investi-

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[12] Analysis of the meaning of a word (Weinhofer, 2010).

gation in corpus linguistics (Rychlý, 2008) and identifies statistically the proximity of semantically similar terms.

$$logDice = 14 + log_2 \frac{2fxy}{fx + fy} \qquad \text{(Equation 1)}$$

Where fx is the number of occurrences of word *x*, fy is the number of occurrences of word *y* and fxy is the number of co-occurrences of words *x* and *y* in the range of ±10 words.

Subsequently, semantic trends were identified by thematically classifying the collocation candidates with components from an established sustainable mining perspective. The five domain framework was selected (DFID, 1999; Cooper and Giurco, 2011), since it includes key areas of concern 'technology', 'economy', 'society' and 'environment' (Dewulf *et al.*, 2015); and is based on the widely established five capital model (Corder, McLellan and Green, 2010), which includes the components: 'technology', 'society', 'environment', 'economy' and 'eligibility', as seen in Table 10. The term 'eligibility' is used instead of governance, since only with a well-defined ownership a process can take place. The five domain framework was expanded to include the 'geological knowledge' of raw materials; for any processing purposes the type, quantity and grade of materials are fundamental considerations (Arndt and Ganino, 2012). I selected 'geological knowledge' as a framework component rather than 'physical and chemical properties' (which 'geological knowledge' depends on), since it reflects a geologist's application of these properties in practice.

3.3.1.3 Establishment of relevant knowledge

The results of the text analysis were employed to generate the conceptual framework (Figure 6). Firstly, the most relevant conceptualisation was based on the highest collocation and the semantically most relevant description. Secondly, the established semantic field was used to identify parallels and establish linkages between mining deposits in the anthroposphere and geosphere. The thematic classes were then assigned to 'accessibility' and its related terms based on the established threshold of 9.00 (see supporting information, section F.2, for details). These classes subsequently provide the fundamental structure of the conceptual framework.

3.3.1.4 Concept extraction

The definition of, and a conceptual framework for, raw material 'accessibility' was extracted from the relevant knowledge (Figure 6), as seen in section 3.3.1.3. This conceptualisation was obtained through the most relevant conceptualisation and thematic classes, which were integrated at the established linkages between mining deposits in the anthroposphere and geosphere.

3.3.2 Evaluation of raw material accessibility

To demonstrate the utility of this framework, I performed an initial evaluation of raw material accessibility using four REE case studies. These case studies were selected, because REE are widely used in modern technologies and are considered critical for their continual supply (Moss *et al.*, 2013). The EoL product case studies from 'deposit' Switzerland encompass: (i) fluorescent lamps containing Europium (Eu); (ii) drive motors from an electric car containing Neodymium (Nd); and (iii) fibre optic cable containing Erbium (Er). The Earth's crust case study includes (iv) the REE deposit, Mount Weld Australia, containing the same three elements. These case studies are described and quantified (within the limits of available data) regarding their 'geological knowledge', 'eligibility', 'technology', 'economy', 'society', and 'environment'. The system is described with components, for which each component is underpinned by one quantitative and one qualitative indicator (Table 7). Collectively these indicators provide an overview of the current situation in terms of raw material supply and are selected on the basis of existing indicators, which were applied in 12 studies that consider material availability (Long, DeYoung and Ludington, 1998; NRC, 2008; Oakdene Hollins, 2008; UNFC, 2010; Graedel *et al.*, 2012; Moss *et al.*, 2013; Neugebauer, 2013; EC, 2014; Tuma *et al.*, 2014; BGS, 2015; Dewulf *et al.*, 2015; Sprecher *et al.*, 2015).

Table 7: Description of the thematic classifications, respectively components, quantitative and qualitative indicators.

Thematic class / component	Definition	Scope	Indicator (quantitative and qualitative)	Unit
Geological knowledge	The understanding of the context of the intended material deposit.	Type, quantity, grade, and mine life at a specific point or extent in space.	Quantitative: mass and mass fraction; Qualitative: description about the level of confidence in the geological knowledge, (i.e. high, medium, low) (UNFC, 2010).	[t], [t/t]
Eligibility Including legislation and policy	The system or form by which a community, company or other political unit is eligible to govern raw materials (adopted from Giurco and Cooper, 2012).	Ownership and regulatory requirements.	Quantitative: World governance indicators (WGI), rule of law (RL), which quantifies the ability of a country to abide the quality of contract enforcement, property rights, and the courts (Kaufmann, Kraay and Mastruzzi, 2010); Qualitative: ownership description along collection/ mining and processing.	[%]
Technology	The application of the knowledge, usage of tools (such as machines or utensils), and techniques to control one's environment.	Collection / mining, and processing of EoL and the Earth's crust (Giurco and Cooper, 2012) with their existing infrastructure.	Quantitative: mining or processing yield; or collection and recycling rate; Qualitative: situation description if no mining, processing or recycling currently exist.	[%]
Economy Including marketing of mining companies	The system of production and distribution and consumption of minerals (Giurco and Cooper, 2012).	Costs, prices of obtaining the material of interest and information on the market stability, i.e. sensitivity or volatility and investments.	Quantitative: processing costs if available, or else raw material price if processing takes place; Qualitative: economic situation description if no mining, processing or recycling exist.	[USD per kg]

Thematic class / component	Definition	Scope	Indicator (quantitative and qualitative)	Unit
Society	Social networks with shared norms, values, and understandings that facilitates co-operation within or among groups (UNU, 2012).	Societal stability, human rights conditions, and working condition .	Quantitative: World governance indicators (WGI), political stability and absence of violence (PV), which quantifies the perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism (Kaufmann, Kraay and Mastruzzi, 2010). Qualitative: description of local social impact monitoring and prevention measures.	[%]
Environment	The natural and resource condition of the nature and ecosystem processes (Giurco and Cooper, 2012).	Climate change, ecosystems, human health and resource depletion.	Quantitative: global warming potential or if data available: life cycle impacts by means of e.g. ReCiPe, ecological scarcity method with environmental impact points (UBP); Qualitative: description of hazardous or radioactive substances and if present, a description on their impact monitoring and prevention measures.	[CO_2eq./kg metal-oxide], [UBP/kg metal-oxide]

3.4 Methodology for Chapter 6

3.4.1 Framework refinement and confirmation

Since the same methods are considered as critically reflected as for Chapter 4, the reflection can be found in section 3.2.1. This reflection aimed at identifying one methodology for the framework refinement and confirmation. It was identified in section 3.2.1 that the Delphi technique is the most suited method for framework refinement and confirmation, as it is easy to coincide in time and space, easier to build groups of experts with the optimal participation number, ensures anonymity, and limited influence among the individual experts (Landeta, Barrutia and Lertxundi, 2011). The evaluation of the confirmation and refinement was carried out by statistical analysis (section 3.4.1.2).

3.4.1.1 Application of Delphi technique

The Delphi technique was used to refine and confirm the relative importance of the 16 sub-components and one to three indicators, i.e. 12 indicators per sub-component, in Chapter 6, Table 20. This application consisted of 3 steps: 1 preparation; 2 Delphi round one; 3 Delphi round two.

Step 1: Preparation. The preparation stage consists of expert selection and development of the Delphi survey (Step 2 and 3 for more information on survey development). The expert selection was a particularly critical step in maintaining the quality of the study, as it directly relates to the generated results (Hsu and Sandford, 2007) and non-uniformity is a potential weakness of this method (Walters and Javernick-Will, 2015). Thus, to choose experts, a 5 point selection criterion was used (Table 8). The criteria were developed on the basis of the intended area of application. This consisted of sustainability, government and policy, professional and academics. To ensure a sufficient number of experts until the end of round two, the experts were oversampled (Walters and Javernick-Will, 2015).

After selection, the experts were contacted to confirm their participation using MailChimp software, an automated e-mail distribution platform (MailChimp, 2018). The experts' first invitation is described in section G.1.1. To obtain a high confirmation rate of the participants, I applied the 'yes ladder' technique, which increased the response rate by 40%. This technique consists of requesting a small task, followed by a big one (Van Petten, 2011). After confirmation, an e-mail with the electronic survey link was sent. The e-mail for the Delphi study round one is in section, and the e-mail for the Delphi study round two is in section G.2.1. After two weeks, a reminder e-mail was sent to the experts, see section G.1.3 for round one and G.2.2 for round two. Round one of the Delphi study one can be found in 'Step 2' and round two in 'Step 3'. As experts were given two weeks of response time for each round, from experience, this time frame was sufficient for a high response rate (Walters and Javernick-Will, 2015). From the 200 contacted experts, 73 confirmed their participation, 58 fully completed round one and 48 fully completed round two of the Delphi study.

Table 8: Expert selection criteria (Keeney, Hasson and McKenna, 2006; Zimmermann, Darkow and von der Gracht, 2012; Walters and Javernick-Will, 2015).

Criteria	Description
Stakeholder type	Academia , private company or government
Expertise	Waste management, industrial ecology or geology that is related to anthropogenic and geological raw material issues. These comprise UNFC classification, criticality assessment and sustainability evaluation
Expertise in relation to evaluation methods of metals	Publications or presentation in this field of expertise
Professional and research experience	Position of job or university and at least 3 years of experience
Publication	Number of publication and presentations at least 5 if less than at least 10 years of experience; otherwise 2.

Step 2: Delphi study round one. The first round aimed to identify the relatively more important sub-components and indicators. For this, the experts were asked to rank the sub-components and their respective indicators based on their perceived importance and given the chance to provide clarifying comments. For the ranking a standard 5 point Likert scale was used in the SurveyMonkey software. The experts were also asked to answer classification questions which included: their field of expertise and employment, metallic raw material or EoL product of expertise, country experience, working experience, age, gender and general remarks (Caron, Durand and Asselin, 2016). The survey questionnaire is in section G.3. The expert participation included regarding the field of expertise included, 28 in industrial ecology, 20 in geology, and 10 in waste management. The field of employment included: 32 in academia, 14 in national government, 10 as private consultants, 1 in a private waste management company, and 1 in a private mining company. All experts had experience related to raw material issues. All experts had experience related to raw material issues.

Step 3: Delphi study round two. The second round aimed to confirm the relative importance of sub-components and their respective indicators. For this I invited the experts to reassess the group's opinions *in lieu* of the aggregated percentile group response and using a 4 point Likert scale, which was reduced by the lowest importance rank. The aggregated group response and 4 point Likert scale was implemented to facilitate a consensus establishment (Quyên, 2014). The reminder of the survey was alike round one. The survey questionnaire is in section G.4. The expert participation regarding the field of expertise included 24 in industrial ecology, 16 in geology, and 8 in waste management. The field of employment included 30 in academia, 9 as private consultants, and 9 in national government. All experts had experience related to raw material issues.

3.4.1.2 Statistical analysis

In both Delphi survey rounds, the results were first analysed regarding frequency of expert response rate, mean and standard error. The standard error provides a confidence level to mean value (Field, 2009). Then two statistical methods were employed: (i) for consensus establishment: Kendall's W. measure of concordance and (ii) for determining the significant difference among the responses: Wilcoxon signed-rank test and Friedman test. (i) The Kendall's W. measure of concordance is a highly recognised coefficient (Okoli and Pawlowski, 2004). This coefficient shows the degree of consensus from very weak to strong agreement between the experts' preferences of sub-components or indicators (Schmidt, 2013). (ii) The Wilcoxon signed-rank test shows the significant difference between two sub-components or indicators (Field, 2014). The Friedman test shows the significant difference between three items (Ongondo and Williams, 2011). From investigating three items in the Friedman test, the pairwise influence of two items to each other is not analysed. To investigate this pairwise influence, the Wilcoxon signed-rank test was applied. The Wilcoxon signed-rank is particularly useful with a Likert scale and small sample sizes (Meek, Ozgur and Dunning, 2007), as applied in this study. These results were analysed by means of Microsoft Excel and Statistical package for Social Sciences – SPSS (Gomes *et al.*, 2014). The Delphi survey was terminated by identifying a significant difference between the results of the last two rounds by means of Wilcoxon signed-rank test (Boulkedid *et al.*, 2011).

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Chapter 4 A geological reconnaissance of electrical and electronic waste as a source for rare earth metals

4.1 Linkage of chapter to PhD research

The Chapter 4 is a partially modified version of the published paper as Mueller *et al.* (2015). This paper is electronically available as an open access publication. This chapter attempts to fill the knowledge gap of developing a structural approach to geologically characterise and evaluate the anthropogenic deposits of EoL products (Velis and Brunner, 2013; Stamp, Anna, 2014). Firstly, a basic framework for connecting the geosphere with the anthroposphere was defined. On this basis, important geological processes were investigated, which understanding were transferred to anthropogenic processes for identifying the most concentrated anthropogenic depositions according to their specific surface area in a country. Secondly, according to existing structured geological characterisations, 'geological settings' of a geological and three anthropogenic deposits were investigated. Lastly, an evaluation of the characterised deposits by means of 'geological knowledge' was conducted. This provides the fundamental 'geological knowledge' that enables to develop a common language between mining deposits in the anthroposphere and geosphere. The investigation of four case studies provides the basis for the case study evaluations in Chapter 5.

4.2 Graphical abstract

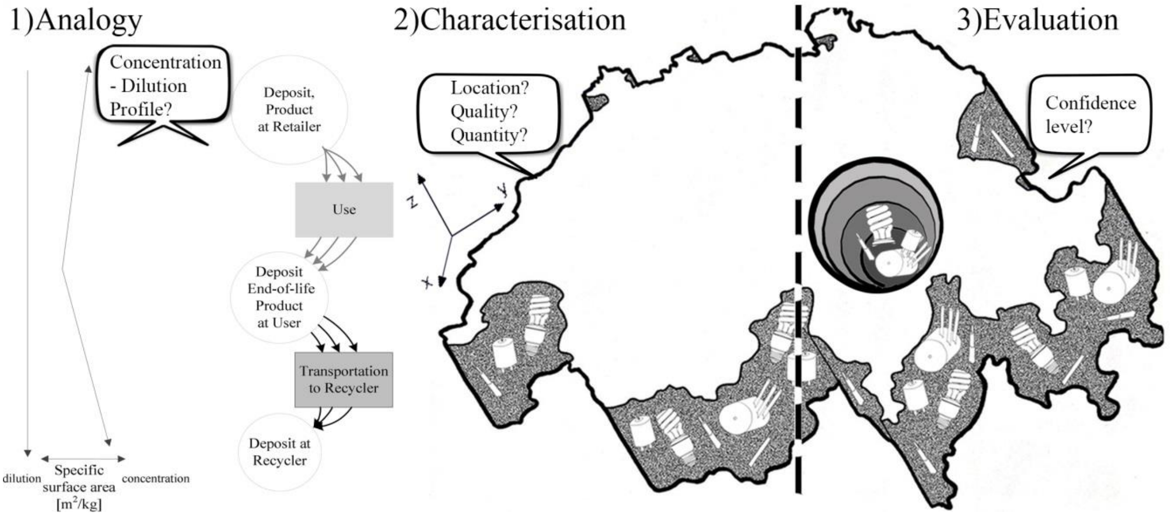

Figure 7: Graphical abstract of research Chapter 4.

4.3 Introduction

Metallic raw materials are crucial to modern society: their mobilisation increased almost 19-fold from 1900 to 2005 (Graedel *et al.*, 2012). With remarkable selectivity, people have sought the local concentration of specific raw materials in the Earth's crust to satisfy increasing demand. Considering the lifespan of the planet, the exploitation of these ores[13] is a recent phenomenon, but it increased exponentially during the last two hundred years (Arndt and Ganino, 2012). Once these geological heritages are consumed, they cannot be replaced in any period significant to human beings (McLaughlin, 1956), since geological mineral deposits are the end product of the prolonged formation of local environmental and geodynamic settings (Dill, 2010). Minerals are individual components within rocks that are generally defined according to their chemical composition and crystal structure (Nickel, 2005). They are the starting point for the production of metals such as REE. REE are considered scarce metals[14] although they are more abundant in the Earth's crust than many other metals (Hoatson, Jaireth and Miezitis, 2011; Wäger *et al.*, 2012). Nevertheless, REE are regarded as prominent geological heritage (Hoatson, Jaireth and Miezitis, 2011), because they have properties required in current and future technologies and presently cannot be substituted by other metals (NRC, 2008; Du and Graedel, 2013). The demand for REE is continually increasing (USDOE, 2011) , with a high risk of supply disruption (Izatt *et al.*, 2014). For example, the demand of Neodymium-Iron-Boron permanent magnets is expected to increase by 12.5% annually until 2035. The use of phosphors with REE is expected to increase at an annual rate of 8% by 2015. Thereafter, an annual decline by 4.5% is expected until 2035 (Alonso *et al.*, 2012). Both of these components, magnets and phosphors, are used in EEE. This use has led to a rapidly increasing volume of REE deposits in WEEE over the last few years (Oswald and Reller, 2011) . With current recycling technologies, less than 1% of the applied REE can be recovered (UNEP, 2011, 2012). Accordingly, today REE follow a nearly linear resource flow from design to eventual landfill disposal along the material life cycle (Curran and Williams, 2012) and are at risk of being dissipated[15] (Wäger, 2011). According to Graedel *et al.* (2011) and UNEP (2010), the material life cycle describes the path of a metal over the various life stages from refining to product manufacturing, to use, EoL, and waste management. Along this path, the metal undergoes several concentration and dilution steps: while refining, the pure metal concentrates, during manufacturing it dilutes slightly and during use the metal dilutes heavily (Wäger, Hischier and Widmer, 2015). Through recovery, the pure metal is concentrated, else further dilution can occur. To move from a linear to a circular material flow (Curran and Williams, 2012), material recovery needs to be facilitated with minimised dissipative losses (Oswald and Reller, 2011). To enhance material recovery in the future, it is pivotal to shed light on the process chain from mining to waste management (Brunner, 2011; Wäger, Widmer and Stamp, 2011; Simoni, 2012; UNEP, 2012). In par-

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[13] Ores are accumulations of metals and minerals at a particular location (McLaughlin, 1956).

[14] (Geochemically) scarce metals are those metals, whose crustal abundance is <0.01 weight-% (Skinner, 1979).

[15] "Dissipation" is understood as the "dilution" of materials into the anthroposphere in such a way that a material recovery is difficult or impossible (Wäger *et al.*, 2012; Zimmermann and Gößling-Reisemann, 2013). The "anthroposphere" includes the living space created and designed by people (Kosmol *et al.*, 2012).

ticular, both mining of the geosphere and anthroposphere require knowledge about mineable deposits (Lederer, Laner and Fellner, 2014). In this research, a framework was developed that allows the establishment of analogies between geological and anthropogenic processes. Based on this framework, analogies between mining of the geosphere and anthroposphere are derived for the case of REE and used to identify the most concentrated deposits for three selected EoL products containing REE components. The three identified deposits are characterised and evaluated with 'geological' approaches.

4.4 Geological approaches for characterisation and evaluation of geological deposits

In geology, deposits are characterised to provide a basic understanding of ore deposits' formation and the abundance of minerals. A characterisation includes different attributes describing geological features, such as the location, geological provenance, host rock, mineralisation, source and age of mineral and genetic modelling (Hoatson, Jaireth and Miezitis, 2011).

On this basis, different classification schemes have been developed that allow a comparison between the different ore minerals (Long, DeYoung and Ludington, 1998). A widely applied scheme is the so-called 'genetic classification' of ore deposits. The genetic classification is based on a description of various mineralisation criteria and/or associated geological events, i.e. ore forming processes (Hoatson, Jaireth and Miezitis, 2011; Pohl, 2011; Arndt and Ganino, 2012).

In order to evaluate mineral reserves and resources, a globally harmonised and universally applicable classification framework has been developed by international experts from different country-specific classification frameworks: The United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC classification) (UNFC, 2010). This classification evaluates resources based on three dimensions: socio-economic viability, project feasibility and geological knowledge. Within this framework, the dimension 'geological knowledge' encompasses four levels, which assign different levels of confidence to the quantities of a deposit (Table 9). For potential mining, both mining of the geosphere and anthroposphere require quantities that can be determined with at least low level of confidence, i.e. between levels G1 – G3. In contrast, if the quantities are only estimated, respectively cannot be determined with a low level of confidence, no mining can commence. Then level G4 is assigned to the potential deposit.

Table 9: Summary of the category geological knowledge of the UNFC classification (UNFC, 2010).

Level	G1	G2	G3	G4
Definition	Quantity of known deposits that can be determined with high level of confidence.	Quantity of known deposits that can be determined with moderate level of confidence.	Quantity of known deposits that can be determined with low level of confidence.	Estimated quantity of potential deposits based mainly on indirect evidence.

4.5 Methodology

A detailed description of this method can be found in section 3.2.

4.6 Results and discussion

4.6.1 Framework development

The identified framework shows the relationship between the perspectives of the 'simplified crust-surface geochemical cycle', 'mining', 'processing' and 'product cycle' (Figure 8). It lays the foundation for establishing analogies between geological and anthropogenic processes.

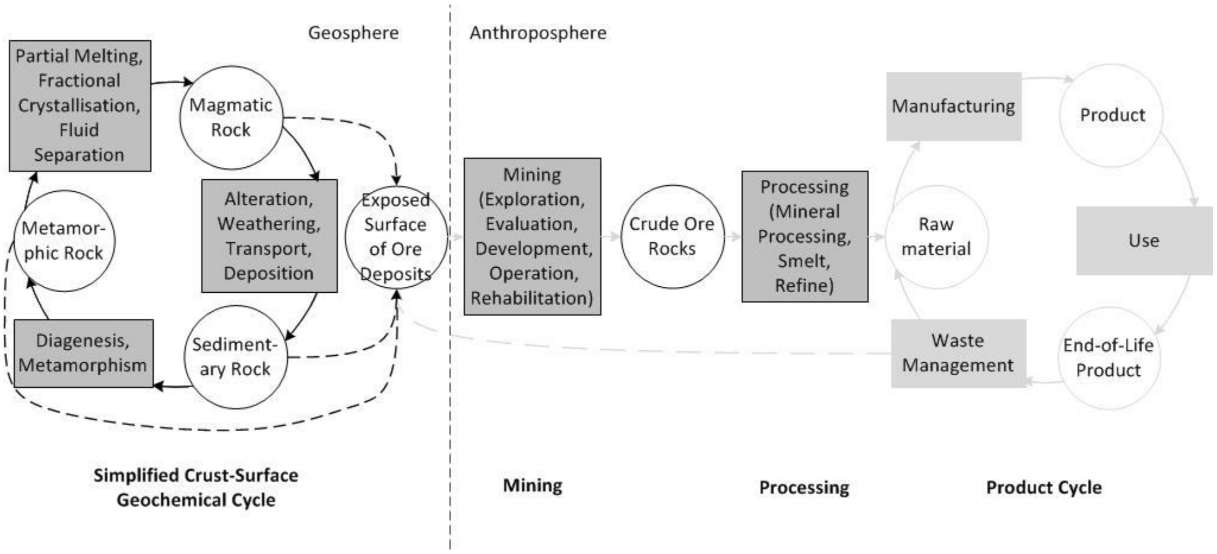

Figure 8: Basic framework connecting the geosphere with the anthroposphere, represented as processes (boxes), states (circles) and connections between the processes and states (arrows).

The framework connecting the geological and anthropogenic cycles can be described as follows:

The simplified crust-surface geochemical cycle adopted from Hoatson, Jaireth and Miezitis (2011) constitutes the foundation of the mining of the geosphere. During this cycle, the 'Magmatic rocks' are ‘altered’ and deconstructed by ‘weathering’, then ‘transported’ and ‘deposited’ as ‘sedimentary rocks’ (Hamblin and Christiansen, 2004). This is followed by a mineralogical modification of the rock structure through ‘diagenesis[16]‘ at low pressure and temperature, and through ‘metamorphism[17]‘ at high pressure and temperature, into ‘metamorphic rocks’ (Kornprobst, 2002). These rocks are melted at high temperature and crystallise into ‘Magmatic rocks’ (Berner and Berner, 2012). Within the crust-surface geochemical cycle, any rocks can potentially be mined.

Mining is the subsequent process. According to Mudd (2009), the mining site has to be ‘explored’ first, which is followed by an ‘evaluation’, e.g. after the mineral reserve/resources classification by UNFC (2010). Then, the mining process needs to be ‘developed’ before the ‘operation’ can commence. Lastly, the mine site needs to be ‘rehabilitated’ to its surface original condition (Mudd, 2009).

In processing, ‘crude ore rocks’ are crushed, ground and separated during ‘mineral processing’, and the concentrated fraction is ‘smelted’ and ‘refined’ to produce the raw material (Wills *et al.*, 2006). **In the product cycle** as described by Du and Graedel (2011), the ‘raw material’ is ‘manufactured’ into a ‘product’ which is ‘used’ until it reaches the ‘end-of-life’ stage. Then, through ‘waste management’ raw material can be produced again, which leads into a new product cycle. Within this cycle the processes ‘manufacturing’ and ‘use’ are for a specific purpose: the use of products. Consequently, these products cannot be mined, with the exception of residues and scraps. In contrast, when a product reaches the ‘EoL product’ deposit, it loses its specific purpose and could be mined. This means that for the processes in ‘waste management’, i.e. starting at the ‘EoL product’ via ‘waste management’ to ‘raw material’, the same principles apply as for genetic deposit understanding and subsequently its classification (Hoatson, Jaireth and Miezitis, 2011).

4.6.2 Identification of analogies

4.6.2.1 Identified analogies

The experts found the analogy between the processes ‘alteration, weathering, transportation, deposition’ and the process ‘use’, and their corresponding concentration – dilution profiles for the geological and anthropogenic, to be most relevant. The transcribed data is in section E.1. Accordingly, this analogy was further elaborated for the case of REE in WEEE, considering the development of the ra-

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[16] Diagenesis is any physical, chemical or biological change undergone by a sediment after initial deposition and rock formation, excluding surface alteration (weathering) and metamorphism. Such changes happen at relatively low temperatures and pressures and result in transformations to the rock's original mineralogy and texture (Árkai, Sassi and Desmons, 2003) .

[17] Metamorphism creates any rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shear stress, and chemical environment, generally at depth in the Earth’s crust (Hoatson, Jaireth and Miezitis, 2011).

tio between the total area occupied by a certain amount of geological and anthropogenic deposit (measured in specific surface area [m^2/kg product or EoL product]), as a possible representation for the (spatial) concentration – dilution or spread profiles.

4.6.2.2 Specification of the geochemical cycle and of the product cycle

To further elaborate on the analogy for REE, the crust-surface geochemical cycle had to be specified Figure 9. The genetic formation of REE consists of four major mineral-system associated geological REE deposits: the 'Magmatic[18]', 'Regolith[19]', 'Basinal[20]' and 'Metamorphic'. These four deposits differ from the three types of rocks identified in the framework (Figure 8). The analogy is formed by specifying the process chain from the 'Magmatic deposit' via the 'Regolith deposit' to the 'Basinal deposit'. The main processes between the 'Magmatic deposits' and 'Regolith deposits' are 'alteration' and 'weathering' Figure 9. The main processes between the followed by deposits 'Regolith' and 'Basinal associated mineral-system' are 'transportation' and 'deposition'. The 'alteration', 'weathering', 'transportation' and 'deposition' processes can either lead to a concentration or a dilution, depending on the circumstances. For example, the existence of a common transportation channel combined with an ideal deposition environment results in spatial concentration, while diverse transportation routes combined with many different options for mineral deposition result in spatial dilution.

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[18] Magmatic material comprises a mixture of molten or semi-molten rock, volatiles, solids, dissolved gas and gas bubbles that is found beneath the surface of the Earth (Sigurdsson, 2000).

[19] Regolith is the unconsolidated material, both weathered in place and transported, which overlies consolidated rocks (bedrock) (Hoatson, Jaireth and Miezitis, 2011).

[20] Basinal is a layer of solid, heterogeneous material that comprises a mixture of sedimented rock or sand. It can also form REE containing heavy mineral sand or sea-floor nodules, respectively manganese nodules (Hoatson, Jaireth and Miezitis, 2011).

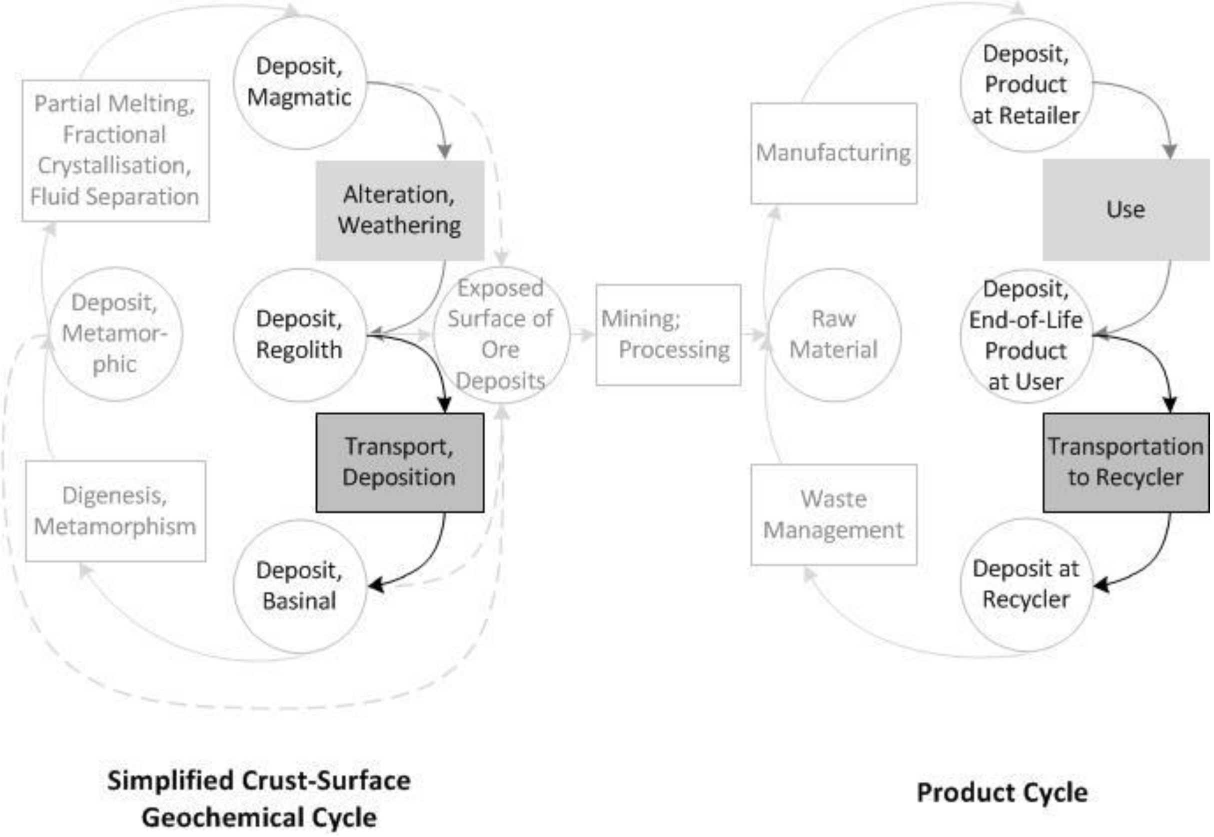

Figure 9: Specification of the framework connecting the geosphere with the anthroposphere for REE. Processes (boxes) related by analogy are highlighted.

Similarly, the product cycle was specified in the three anthropogenic deposits, ‘product deposit at retailer’, ‘EoL deposit at user’ and ‘deposit at recycler’ and the two processes ‘use’ and ‘transportation to recycler’ between these deposits. The ‘use’ process was identified to correspond to ‘alteration’ and ‘weathering’, the ‘transportation to recycler’ process to ‘transportation’ and ‘deposition’. Consequently, the ‘use’ phase is characterised by changes in a local environment with specific boundaries, e.g. using a product in a country. The used products can become concentrated at their EoL (in this chapter, this term is used to mean the point at which the last holder no longer has any use for the item).This can lead to the formation of the ‘EoL deposit’. Such anthropogenic ‘deposits’ are generally formed at each product user. Considering the much larger number of users than manufacturers, scarce metals contained in products are spatially diluted or higher spatial spread (Figure 10). EoL products can be ‘transported’ and form a ‘deposit at recycler’. The far smaller number of recyclers compared to consumers result in a spatial concentration or lower spatial spread.

4.6.2.3 Synthesis of analogies for selected REE EoL products

Three REE EoL products were selected as case studies for an exemplary application of the analogy on anthropogenic deposits. All products are used in a different local environment, i.e. their use is either mobile, stationary or inaccessible. The first, Neodymium, is contained in Neodymium-Iron-Boron permanent magnets used in (electrical) cars, which are mobile during their use and at their EoL are ‘transported’ to recyclers at fixed locations for depollution and dismantling. The second, Europium, is contained in phosphors mainly used in fluorescent lamps that are fixed during use and also transported to recyclers for processing. The third, Erbium, is contained in optical fibres used mainly in underground cables.

Figure 10 a-c shows the concentration – dilution profiles for the three case studies addressed. For Neodymium-Iron-Boron permanent magnets and phosphors fluorescent lamps, the concentration decreases from the ‘deposit at retailer’ to the ‘EoL deposit at user’, while it increases again from the ‘EoL deposit at user’ to the ‘deposit at recycler’. For underground fibre optic cables, the concentration decreases from the ‘deposit at retailer’ to the ‘deposit EoL at user’; there is no ‘deposit at recycler’, because a collection system currently does not exist.

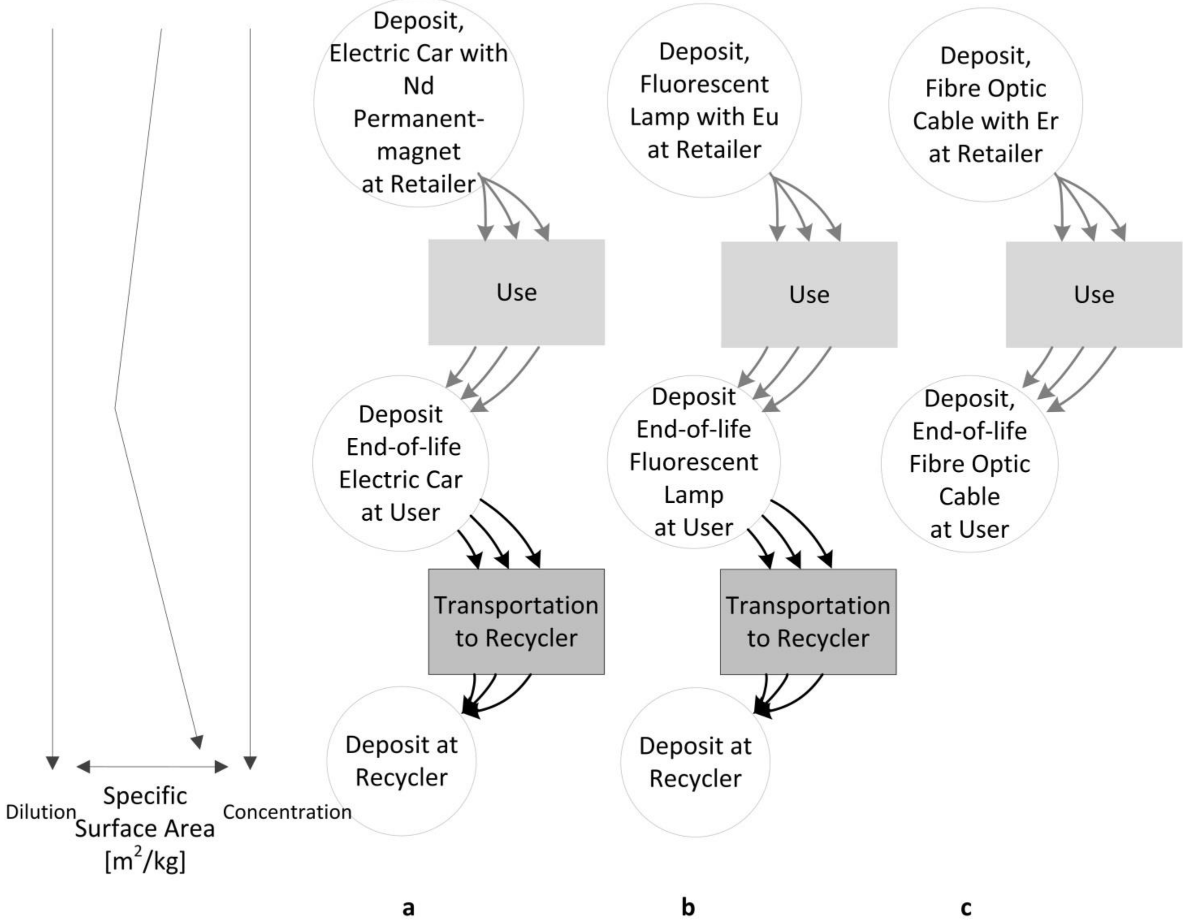

Figure 10: Concentration – dilution profile for the three case studies addressed a: Electrical car with Neodymium-Iron-Boron permanent magnets; b: Fluorescent lamp with phosphors containing Europium; c: Underground fibres optic cable doped with Erbium. The specific surface area shows the dilution, concentration changes along the material cycle from retailer, user to recycler. In each of the three case studies represent the number of arrows and indication on the concentration at the surface area.

4.6.3 Development of characterisation and evaluation approach for selected REE EoL products

For each of the three case studies the geological setting was characterised according to the criteria defined in Table 10. For the characterisation, the anthropogenic deposits with the maximal concentration, i.e. lowest spread, of REE EoL products were chosen, i.e. the ‘deposit at recycler’ for the electric car with Neodymium-Iron-Boron permanent magnet and the fluorescent lamp, and the ‘deposit EoL at user’ for the fibre optic cable.

Table 10: Criteria characterising the 'geological setting'.

Criteria	Explanation	
	Geological perspective	Product cycle perspective
Location	Short overview of the place of the geological or anthropogenic deposit.	
Geological context	The process of the formation of the geological area around the deposit, with focus on identifying potential 'host rocks'. An illustration can be included to visualise the formation of the 'host rock'.	The process of the formation of the local environment of the deposit, with focus on identifying potential host product group, e.g. laptop. An illustration can be included to visualise the location of the 'host rock/product group'.
Host rock	The process of the formation of the rock, which contains the sought resource, to gain an understanding of the forming process to enable discovery of other deposits with the same 'host rock'.	The process of building the product component, e.g. laptop screen, which contains the sought resource and potential hazardous substances, to gain an understanding of the matrix forming process, to allow for the discovery of other deposits with the same host product components.
REE mineralisation	The process of concentration and its resulting specification of the existing mineral to obtain a detailed understanding of the formation of the ore to estimate the grade thereof.	The process of past, current and expected concentration of the resource and potential hazardous substances and their resulting specification; e.g. mineralisation of materials in laptop screen, to obtain a detailed understanding of the formation of the resource to estimate the grade thereof.
Age of mineralisation	The period when the deposit was formed, or when the mineral was concentrated. This belongs to a	The period when the deposit was formed and its expected future growth, e.g. formation time of a laptop

Criteria	Explanation	
	Geological perspective	Product cycle perspective
	general description of a deposit; it can enable an indication of where other similar deposits were formed during the same period of mineralisation. This is relevant for both local and global deposits.	deposit. This gives a general overview of the age of deposits but also indicates future deposits both locally and globally.
Current status	The current development state of the geological or anthropogenic deposit with regard to potential mining, and information on the mine life if available.	

Table 11: Characterisation of the 'geological setting' for geological and anthropogenic deposits.

Criteria / Deposit	Mt. Weld, Australia	Neodymium-Iron-Boron permanent magnet	Europium (Eu) phosphors	Erbium (Er) fibre optic cable
Geological and anthropogenic deposit location	Mined deposit with REE in Mt. Weld in Western Australia.	Deposit at recycler of electrical car with Neodymium-Iron-Boron permanent magnet in Switzerland.	Deposit at recycler of fluorescent lamp with Eu phosphors in Switzerland.	End-of-life deposit of fibre optic cable doped with Er in Switzerland.
Geological context	A steeply plunging cylindrical carbonatite complex enclosing REE, which intrudes the central part of the linear graben-like zone. This zone has been overprinted by greenschist facies[1] metamorphism in Yilgarn Craton, Western Australia.	>70 end-of-life vehicle (ELV) recycling sites (Figure 11) (Blaser, Widmer and Wäger, 2012).. The number of recycling business is increased in urban areas. They sort the vehicle into spare parts and scrap (Blaser, Widmer and Wäger, 2012).	Four recyclers (Figure 11) under contract by an independent Swiss Light Recycling Foundation: SLRS (Empa, 2012). The recyclers separate the end-of-life fluorescent lamp into four fractions: aluminium-end-cap, glass chips glass-fraction and distilled phosphors, which last two fractions contain mercury (Hug and Renner, 2010).	Implemented along the road and train network until it reaches a building with elevated concentrations in urban areas and between cities. In urban areas the hotspots occur at roads, businesses hubs and public organisations.

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[1] Greenish rock that is formed under the lowest temperatures and pressure usually produced through regional metamorphism (Encyclopaedia Britannica, 2014).

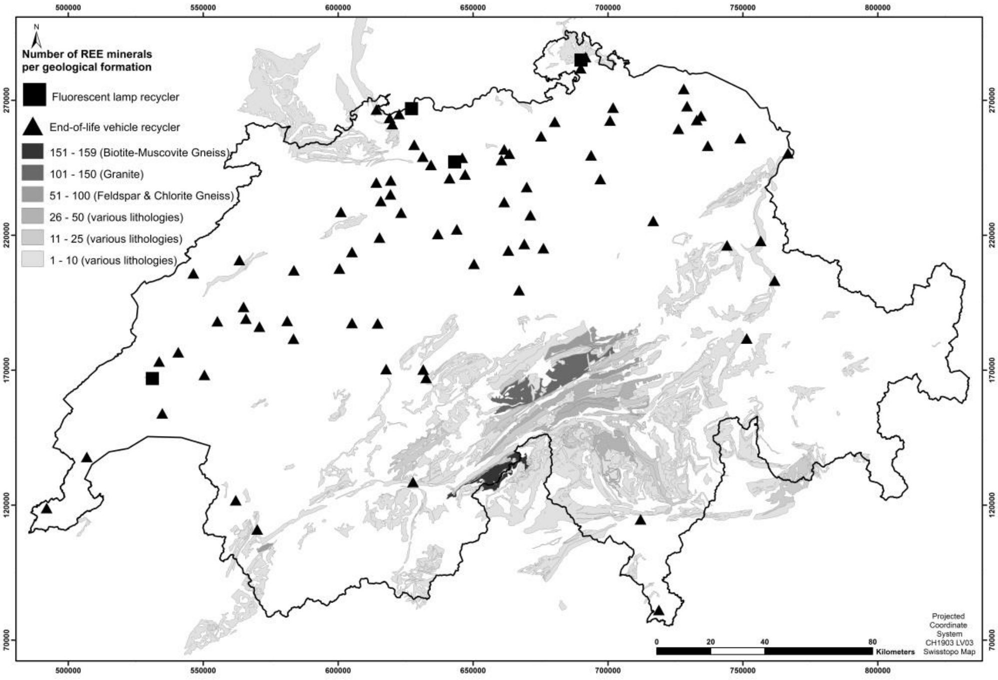
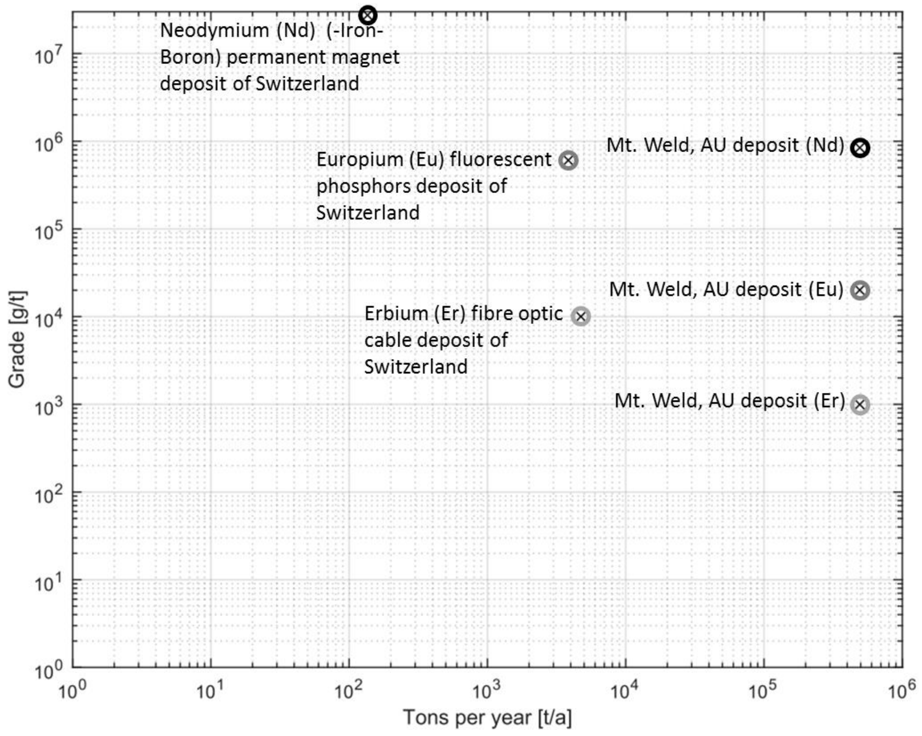
<table>
<tr><th>Criteria / Deposit</th><th>Mt. Weld, Australia</th><th>Neodymium-Iron-Boron permanent magnet</th><th>Europium (Eu) phosphors</th><th>Erbium (Er) fibre optic cable</th></tr>
<tr><td></td><td colspan="4">

Figure 11: Simplified illustration of the geological and anthropogenic REE deposits in Switzerland. The potential geological deposit includes the geological formations that have the highest REE mineral counts (grey nuances with rectangle legend) and the anthropogenic deposits of end-of-life vehicle recycler (Nd, triangles) and fluorescent lamp recycler (Eu, squares) (Empa, 2012; Simoni, 2012; SwisscomDirectories, 2012).</td></tr>
<tr><td>Host rock</td><td>The carbonate has been leached and removed by groundwater activity, thus the relict igneous minerals concentrated. The remaining rock encloses phosphates, iron and manganese bearing oxides containing evaluated REE but also the radioactive elements uranium and thorium.</td><td>Electrical car motor hosts the Neodymium bearing permanent magnet (Du, <i>et al.,</i> 2015). The motor is placed at the back or front of a car. Within a motor the Nd can be concentrated at various positions, depending on the design of a motor.</td><td>Inside a fluorescent lamp, the Eu and mercury are hosted at elevated mass fractions within the phosphors. In the phosphors, the Eu is homogeneously distributed.</td><td>The fibre optic cable is part of underground pipelines and building connections that hosts the Er. It is protected with several layers of slipcovers to prevent cracking but enable bending. The quartz glass is doped with Er (Angerer, 2009a).</td></tr>
</table>

Criteria / Deposit	**Mt. Weld, Australia**	**Neodymium-Iron-Boron permanent magnet**	**Europium (Eu) phosphors**	**Erbium (Er) fibre optic cable**
REE mineralisation	The central lanthanide deposit contains in the carbonatite complex (9.88 Mt @ 10.7weight-% rare earth oxides (REO), 0.85weight-% Nd, 0.02weight-% Eu, 0.001weight-% Er, (Figure 12). Very high-grade mass fractions of REO in the Regolith result from secondary monazite in polycrystalline aggregates.	By 2030, the Neodymium-Iron-Boron permanent magnet deposit is expected to contain $Nd_2Fe_{14}B$ 2,691t @ 27weight-% Nd and 15,143t @ 27weight-% Nd by 2050 (Haan, Zah and Althaus, 2013), (Figure 12). The amount of magnet depends strongly on the application of the motor.	The distilled phosphor includes Eu as Eu_2O_3 but also the REE: yttrium, lanthanum, cerium, gadolinium, terbium and mercury. In 2011, this deposit contained 22,287t @ 0.6weight-% Eu (Schüler *et al.*, 2011), (Figure 12). In 2030, it is expected to contain 76,420t @ 0.6weight-%.	In 2009, fibre optic cable deposit contained 15,551t (Müller, *et al.,* 2013) @ 0.01weight-% Er (Hering, 2006), (Figure 12). In 2030, it is expected to contain 95,000t @ 0.01weight-% Er.
	 **Figure 12: Grade-tonnage plot of annual REE material resource flows form geological and anthropogenic deposits. Corresponding geological and anthropogenic deposits shown in the same grey scale (black: Nd case study, grey: Eu case study, light grey Er: case study).**			
Age of mineralisation	The carbonatite intrusive was part of a local alkaline magmatic event about 2025 million years ago.	At the end of 2010, the first series of electrical cars with Neodymium-Iron-Boron permanent magnet	The fluorescent lamp with Eu has been patented in 1973 (Blasse and De Vries, 1973). The demand	Fibre optic cable with Er was described in 1990 (Suzuki, 1990 in Yoneyama, 1994).The

Criteria / Deposit	**Mt. Weld, Australia**	**Neodymium-Iron-Boron permanent magnet**	**Europium (Eu) phosphors**	**Erbium (Er) fibre optic cable**
	This carbonate intrusive was concentrated by a Permian glaciation event, which allowed the surface of the rich carbonatite intrusion to be exposed for concentration. This event is understood to have occurred about 65.5 million years ago.	were introduced into in the mass market. The breakthrough of one million electrical cars produced is estimated to be in 2017 (Haan, Zah and Althaus, 2013). It is estimated these deposits may increase in the future more than 700% (Alonso *et al.*, 2012).	for Eu is expected to increase during the switch from high-volume halogen fluorescent lamp to compact fluorescent lamp (USDOE, 2011; Binnemans *et al.*, 2013). It is expected that the volume of Eu deposits will increase in the future.	average mine life is expected to be 50 years (Müller, *et al.,* 2013) and an exponential application growth at least until 2030 (Angerer, 2009a).
Current status	Advanced economic deposit including stockpiling of different grade ores in 2011. In 2012 temporary operating license enabled chemical separation in Malaysia to produce the REO (Machacek and Fold, 2014). The mine life is expected to be at least 20 years.	The motors of electrical cars are currently shredded by metallic machineries. The recovery of Neodymium-Iron-Boron permanent magnet is currently under research for reuse and recycling (Schüler *et al.*, 2011). Additionally, there is yet no commercial recovery development (Binnemans *et al.*, 2013).	Currently, the phosphors including Eu is disposed underground with the option for retrieval (Huber and Schaller, 2013). However, in September 2012, Europium recycling facilities commence its operation (Solvay, 2012).	Currently the fibre optic cable is implemented for its use and it is estimated that it is unlikely to develop any recycling by 2030 (Angerer, 2009a).

This characterisation of the 'geological setting' allows a better understanding of the recycling and disposal phase of an EoL product, as the examples demonstrate. In particular, it allows the identification of potential for reducing dissipation of the anthropogenic deposits. It further enables a product-centric perspective, as proposed by UNEP (2012), because the focus of characterising the 'geological setting' begins with the product, e.g. electrical car (Table 10). For the three case studies investigated, the characterisation of the 'geological setting' demonstrates that:

- there are geological REE within Switzerland held as ores in the 'host rock' but they will not be economically exploitable (Simoni, 2012) within a reasonable time frame.
- the total quantity of REE in the anthropogenic deposits in Switzerland is much smaller than in a geological deposit but with higher mass fraction of raw material, and therefore likely to be more economically viable (Figure 12).

The quantity and mass fraction of REE within the investigated anthropogenic deposits of Switzerland and within one geological deposit Mt. Weld in Australia are,

- Neodymium: 2,691t deposit Switzerland @ 27 weight-% and 9.88 Mt central lanthanide deposit Mt. Weld Australia @ 0.85 weight-%;
- Europium: 76,420t deposit Switzerland @ 0.6 weight-% and 9.88 Mt central lanthanide deposit Mt. Weld Australia @ 0.02 weight-%; and
- Erbium: 95,000t deposit Switzerland @ 0.01 weight-% and 9.88 Mt central lanthanide deposit Mt. Weld Australia @ 0.001 weight-%.

Furthermore, the anthropogenic deposits of Neodymium-Iron-Boron permanent magnets and fibre optic cable with Er (Angerer, 2009a) are expected to grow for at least the next 20 years, which is more than the current estimate of 20 years mine life of the Mt. Weld geological deposit (Hoatson, Jaireth and Miezitis, 2011). Additionally, mining the REE held in these so-called 'anthropogenic deposits' is likely to involve considerably fewer social and environmental impacts than the extraction from the present major mined, geological deposits (Alonso *et al.*, 2012). These geological deposits often contain accumulations of radioactive thorium and uranium (Hoatson, Jaireth and Miezitis, 2011).

Considering the high mass fractions, long mine life and fewer social and environmental impacts with the expected supply constraints of Nd (Roelich *et al.*, 2014) and Eu (USDOE, 2011), which both have limited or no substitution options (Graedel *et al.*, 2013), it is important to develop strategies and a common platform between mining of the geosphere and anthroposphere. Furthermore, for Neodymium-Iron-Boron permanent magnets, the results demonstrate that with the current recycling technology of metallic shredders Nd cannot be recovered (Widmer *et al.*, 2015). Considering the high mass fractions, at present only the Er within the fibre optic cable in Switzerland can be considered as geochemically scarce. Since the Er fibre optic cable applications are expected to increase exponentially (Angerer, 2009a), the Er will be distributed and consequently diluted further within Switzerland's ground and buildings until after 2030.

The characterisation of the 'geological setting' of anthropogenic deposits was demanding. The criterion 'host rock' can be valid for different levels of product components. For example, considering an electrical car with Neodymium-Iron-Boron permanent magnets, the 'host rock' could apply to the electrical car and also to the motor. In such a case, a bottom-up approach was applied. For this, first the 'REE mineralisation' was identified, i.e. Neodymium-Iron-Boron permanent magnet, followed by the resulting 'host rock', i.e. motor. To increase the accuracy of characterising the 'host rock' or 'mineralisation', it is important to exchange transparent information through the entire 'product cycle' from design via manufacturing to waste management. For instance, the implementation of a feedback loop from end-of-life to decision makers is limited (Fakhredin *et al.,* 2013). Information on such matters is critical in determining a comprehensive understanding of 'age of mineralisation', which includes the future growth of a deposit formation. This, in turn is important for identifying the economic viability of a future mine (UNFC, 2010). Hence, key performance indicators are a central support for a practical implementation and should be physically-, economic- and environmentally-based as proposed by the UNEP (2012). Moreover, Winterstetter *et al.* (2015) concluded that future research is required to develop a standardised procedure for characterising any kind of geological and anthropogenic deposits,. Additionally, it is central to develop a common platform for characterising and evaluating geological and anthropogenic deposits. Therefore, the characterisation of the 'geological setting' and its evaluation of the 'geological knowledge' (Table 12) lay a foundation.

Based on this foundation, the evaluation showed that, the Neodymium-Iron-Boron magnets and the fibre optic cables can be considered to be potential deposits for Nd (category G3) and Er, respectively (category G4). The deposit containing Eu is classified as a known deposit of category G1 like the geological deposit Mt. Weld. This is a first step in completing the level of proven resources for developing a mining of the anthroposphere mine, as described for mining of the geosphere (Hoatson, Jaireth and Miezitis, 2011; USDOE, 2011).

Table 12: Evaluation of 'geological knowledge' of geological and anthropogenic deposits, adopted from UNFC (2010).

Criteria	Geological deposit Mt. Weld, Australia with REE	End-of-life of electrical car with Neodymium-Iron-Boron permanent magnet	End-of-life fluorescent lamp with Europium	End-of-life optic cable with Erbium
Category	G1	G3	G1	G4
Supporting explanation	Mining has commenced in for stockpiling in 2011 and separation in 2012.	The application is being introduced in the market, thus information of future scenarios including uncertainty is available. Research for recovery is currently being undertaken. No commercial recovery takes place yet.	Information on the future development of the deposit quantity is available. Recovery activities commenced in 2012.	Low information on the precise location of the quantity is available. Currently no research for the recovery is being undertaken.

4.7 Conclusions and outlook

In this study, I have attempted to integrate a geological perspective and approaches into the characterisation and evaluation of anthropogenic metal deposits. This approach allowed the identification of the most concentrated deposits along the anthropogenic cycle, their characterisation with regard to the 'geological' setting, and the evaluation of the confidence level of the deposit quantities for three cases. Not least, the study was able to provide distinct characterisations for the three investigated REEs. However, the present framework is built on a simple representation of the reality, as e.g. raw material losses (for example REE in fibre optic cables left in the underground) are not represented. A possible next step consists of further differentiating the processes and exploring how far correspondences between the geological and anthropogenic cycles can then still be established. This is addressed in Chapter 5.

Chapter 5 A framework for evaluating the accessibility of raw materials from end-of-life products and the Earth's crust

5.1 Linkage of chapter with PhD research

The Chapter 5 is a partially modified version of the published paper as Mueller *et al.,* (2017). This paper is electronically available as an open access publication. This chapter addresses the lack of research concerning the resilient and quantitative evaluation of scarce metals (Stamp, 2014; Velis and Brunner, 2013). Consequently, this chapter attempts to fill this knowledge gap by presenting an investigation into the quantitative characterisation and evaluation of scarce metal accessibility under sustainability considerations. Based on a systematic concept extraction, the current use and meaning of the term accessibility was investigated. This resulted in the proposal of a new definition, a conceptualisation and a quantitative characterisation and evaluation of scarce metals from EoL products and the Earth's crust through case studies. This initial quantitative characterisation and evaluation applies, based on the literature review, 7 identified indicators. These indicators were selected by means of most frequently used in the reviewed availability evaluation approaches and quantifiable, despite the limited available data. These selected quantitative indicators are denoted in Table 4. The case studies in turn provide a solid foundation for Chapter 6.

5.2 Graphical abstract

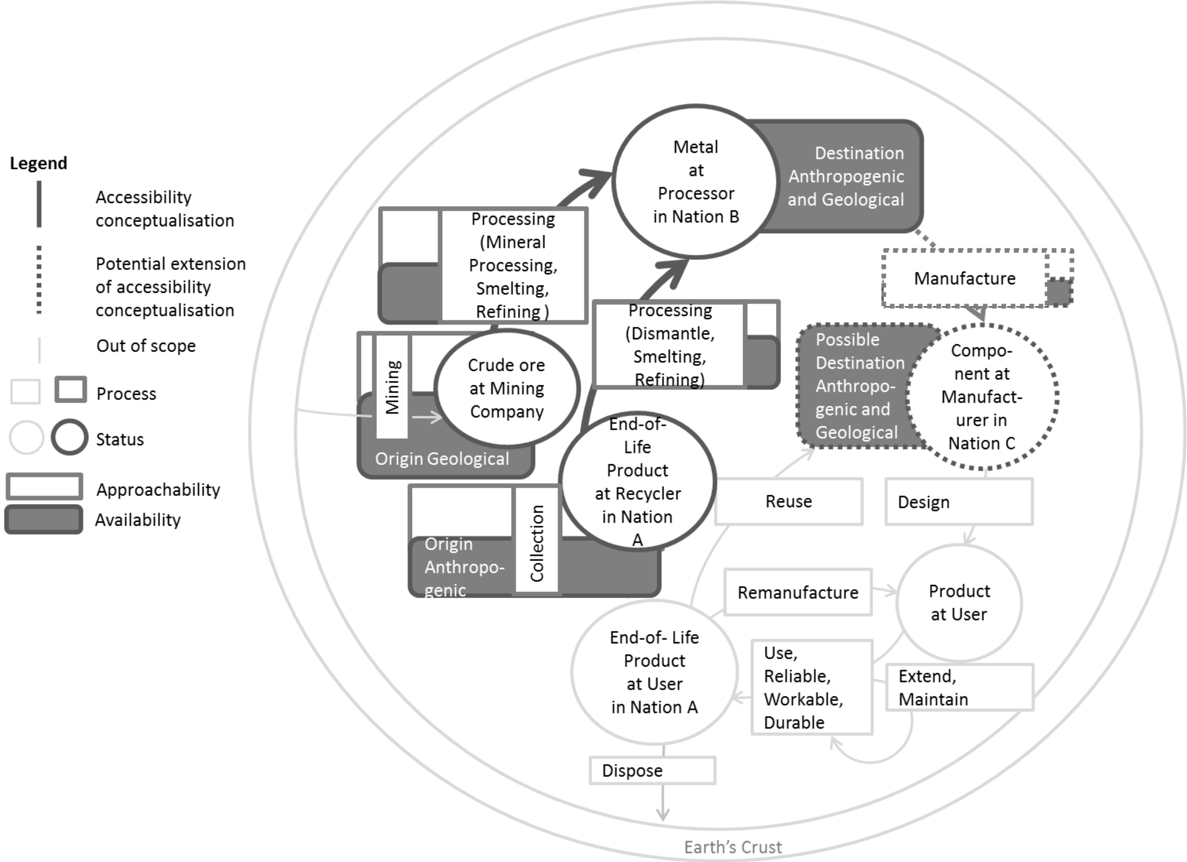


Figure 13: Graphical abstract of research Chapter 5.

5.3 Introduction

Due to continuing technological advancement, an increasing number of scarce metals[22] are entering into our daily lives. With a reversal of this trend not foreseeable (Zepf *et al.*, 2014), there are growing concerns for the security of raw material supply. For many raw materials, the supply situation is considered critical due to: (i) their production being concentrated in a few countries (Simoni *et al.*, 2015), (ii) limited options for appropriate substitutes (Graedel *et al.,* 2013), and (iii) very low recycling rates for these materials (UNEP, 2012). To improve the long-term sustainability[23] of critical material supply (Giurco *et al.*, 2014), there is a view that raw material management needs to be rethought (Ongondo, Williams and Whitlock, 2015). Specifically, raw material management needs to consider the mining of

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[22] 'Scarce metals' are those metals whose crustal abundance is <0.01 weight-% (Wäger *et al.*, 2012).

[23] 'Sustainability' means in this study "certainly a sustainable society would use non-renewable gifts from the Earth's crust more thoughtfully and efficiently than the present world does. It would price them properly, thereby keeping more of them [accessible to] future generations. But there is no reason not to use them, so long as their use meets the criteria of sustainability already defined, namely that they do not overwhelm a natural sink and that renewable substitutes are developed." (Meadows, Randers and Meadows, 2004).

materials from both the geosphere and the anthroposphere. To ensure comparability and consistency, both MDA and MDG approaches should be developed and evaluated in parallel. In the cycle of a material, a parallel development and evaluation requires the establishment of linkages between mining deposits in the geosphere, anthroposphere and the subsequent processing. In this sense, for both the MDA and MDG, knowledge of the material (e.g. physical and chemical properties, element concentration, and abundance) and knowledge about potential economic viability is required (Brunner, 2008).

Raw material supply has previously been evaluated based on the 'availability' of materials (UNEP, 2013b; USDOE, 1996). Evaluation of material availability can be based, for example, on the 'geological knowledge' (UNFC, 2010). Availability can also be evaluated through material criticality assessment, which assesses raw material supply based on two functions: their 'availability' and 'importance of uses' (Graedel *et al.*, 2012). Studies of material availability show a large degree of variability in how availability is defined.

It has been suggested that material availability evaluation is too narrow in its scope and that evaluation of raw material supply should be expanded to consider the 'accessibility' of materials (USDOE, 2006). Cook and Harris (1998), for example, recommend that such an evaluation should consider environmental, legal, social, and political aspects in addition to an evaluation of project feasibility. This would be particularly important for materials that are currently unavailable but approachable. Materials in this category include for instance the large amounts of illegally-exported raw materials from End-of-Life (EoL) products, such as obsolete Waste Electrical and Electronic Equipment (WEEE) from the European Union (Huisman *et al.*, 2015). Rankin (2011) adds that it is important to understand, how access to raw materials will change in the long-term. Gruber *et al.* (2010) considered raw material 'accessibility' in relation to policies about raw materials at the European level and they concluded that indicators and specific targets for raw material conservation remained absent. Accessibility has further been applied to evaluate product recycling, specifically in identifying the relevant product parts for dismantling (Hagelüken, 2014) and in geological mining, where 'accessibility' has been used to describe the physical path to a deposit (Weber, 2015). At a systems level, individual aspects of evaluating raw material accessibility have been implicitly included in the fields of economic geology. For instance, accessibility has been integrated in resource classification frameworks (Cook and Harris, 1998) and ecological and social sustainability studies (MacDonald, 2015).

There is need to advance the management of raw materials at different levels. Firstly, there is a lack of consistency in how the terms 'availability' and 'accessibility' are used in studies of raw material supply and what these terms actually mean (USDOE, 1996). Clarification of fundamental terms used in the evaluation of raw material supply is required before a commonly agreed, rational raw material mining strategy can be developed (Cossu and Williams, 2015; Winterstetter *et al.*, 2015). Secondly, although different efforts have been undertaken to link quantitative characterisation and evaluation methods across different disciplines, there is a lack of a broadly applicable assessment approach for a potential sustainable supply of raw materials (Haines *et al.*, 2014). Thirdly, there is a deficiency in a strategy that evaluates the different operational steps along the collection/ mining, processing for continual sourcing of raw material (Roelich *et al.*, 2014). Fourthly, there is need for consistent quantitative evaluations for elements with few available data such as rare earths (Gleich *et al.*, 2013; Weber, 2013). This is particularly important for implementing new waste management regulations, such as the currently revised Swiss 'ordinance for the return, take-back, and disposal of electrical and electronic equipment' (ORDEE). The future ORDEE will require for the first time the recovery of scarce metallic elements from technological equipment wherever possible (FOEN, Federal Office for the Environment Switzerland, 2013).

In this chapter I aim to establish a consistent framework for evaluating raw material supply from both anthropogenic and geological sources at an early project development stage. The objectives were to:

(i) Systematically investigate the use of fundamental terms in the evaluation of raw material supply;

(ii) Develop a novel, consistent framework for evaluating the supply of raw materials; and

(iii) Demonstrate the utility of the developed framework by evaluating the raw material supply in four rare earth element (REE) case studies.

5.4 Method

A detailed description of this method can be found in section 3.3.

5.5 Results

5.5.1 Extraction of conceptual framework

5.5.1.1 Pre-processing

Based on the reflected definitions from the Britannica Academic Dictionary (2014); Cambridge Dictionaries Online (2014); Oxford Dictionary (2014), the definition proffered by WordNet (2014) was found to cover succinctly the key facets of each of the above definitions. 'Accessibility' can semantically be considered to occupy the intersection between 'availability' and 'approachability' (see Supporting information, section F.3 for details).

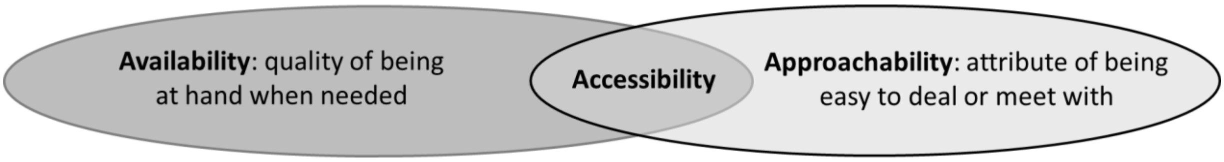

Figure 14: 'Accessibility' is defined by comprising both synonyms 'availability' and 'approachability'; 'accessibility' is located at the intersection.

The pre-processing stage revealed that, whilst 'availability' is commonly referred to in discourse, reference to 'approachability' is rare. This definition of 'accessibility' for raw material supply is shown in Table 13.

The three resulting corpora encompassed: (i) EC 18 documents; (ii) MA 141 documents; and (iii) MG 116 documents.

5.5.1.2 Text analysis

Structural analysis

Both raw material 'accessibility' and 'availability' were found to be rarely used other than in the one example of mineral policy research Tiess (2011), in which raw material 'accessibility' describes policy situations: "Geological availability does not necessarily mean access to raw materials for the mining companies" (Tiess, 2011).

Statistical analysis

For the EC corpus, 'accessibility' was found to be used extensively in urban planning and economic geography. The distribution analysis shows the higher relative word frequency was 1.0% to 3.2%. This included the terms: information, accessibility, access, assurance, data, and planning (Figure 15a). For the MA corpus, the word coverage of < 0.40% showed a low relative word frequency, which was confirmed by showing no 'accessibility' related term in the tag cloud (Figure 15b). For the MG corpus, the word 'accessibility' showed a low relative word frequency of fewer than < 0.10% in most documents. No 'accessibility' related term was among them (Figure 15c) (see Supporting information, section F.4, for details.

Figure 15: Relative distribution of the word frequency. The more frequently a term is used, the bigger the term becomes in relation to the other terms. (a) Corpus: existing conceptualisations (EC); (b) corpus: mining the anthroposphere (MA); (c) corpus: mining the geosphere (MG).

The statistical word coverage investigation of availability showed that, in most documents, 'availability' was found with a coverage of < 0.1%.

Semantic analysis

The semantic comparison of accessibility in the EC corpus showed that accessibility originates from a number of subject areas, including urban planning, economic geography, and information sciences. At a system level, geology comprises raw material availability only (see Supporting information for details). The resulting semantic field demonstrated the root term 'ability' was able to be linked to the cycle of a material (see Supporting information, section F.6, for details).

In the semantic collocation analysis of accessibility, for the corpus EC a logDice value of >10 resulted. The terms with the highest collocated values to ‘accessibility’ were ‘measure’ and ‘indicator’. However, a lower collocation results from the corpus MA with a logDice value of 7.76. Here the closest collocations to ‘accessibility’ were ‘availability’ and ‘metallurgical’. In the MG corpus, use of the word ‘accessibility’ occurs only twice and consequently no logDice value could be established. The adopted collocation analysis shows this term occurs 8 times. The resulting high collocation was in ‘infrastructure’ (logDice score = 11.63) (see Supporting information for details). The collocation analysis of availability is shown in the Supporting information for details.

5.5.1.3 Establishment of relevant knowledge

For developing this framework, the conceptualisation in urban planning was considered implementable. Comparable operation steps between mining deposits in the anthroposphere and geosphere were established as: ‘collection of EoL products’ to ‘mining the Earth’s crust’, followed by ‘processing of components’ to ‘processing of crude ore’, and the joint operation step ‘manufacturing of metal’. From the semantic analysis, the relevant thematic classes to availability were identified as ‘geological knowledge’ and ‘eligibility’. I referred to the standard definition of ‘accessibility’ for allocating the other relevant thematic classes. The most relevant classes were found to be ‘technology’, ‘economy’, ‘society’, and ‘environment’. These thematic classifications will henceforth be referred to as ‘components’ (see Supporting information, section F.9, for details).

5.5.1.4 Concept extraction

This definition for raw material supply is shown in Table 13. To quantify raw material accessibility at each process step, both ‘availability’ and ‘approachability’ need to be determined during the operational steps: EoL product at recycler, crude ore at mining company and processability, (Figure 16). Processability is the first common process for both mining deposits in the anthroposphere and the geosphere. The next destination could be either ‘metal at processor’ or extended to ‘component at manufacturer’; ‘manufacturability at manufacturer’ could thus be included in ‘approachability’. ‘Reusability’, ‘remanufacturability’, and ‘designability’ are deemed out-of-scope, since access to the raw material applies to the end states ‘metal’ or ‘component’. Consequently, the processes ‘usability’, ‘extendibility’ and ‘maintainability’ were also excluded, since a product can only be mined after it reaches its end-of-life (see Supporting information, section F.9, for details).

Table 13: Definition of accessibility for raw material supply.

Accessibility	Raw materials are accessible if there are no 'significant' constraints (e.g. ownership, protected areas, environmental restrictions) to 'get to' the material of interest in order for potential treatment or production.

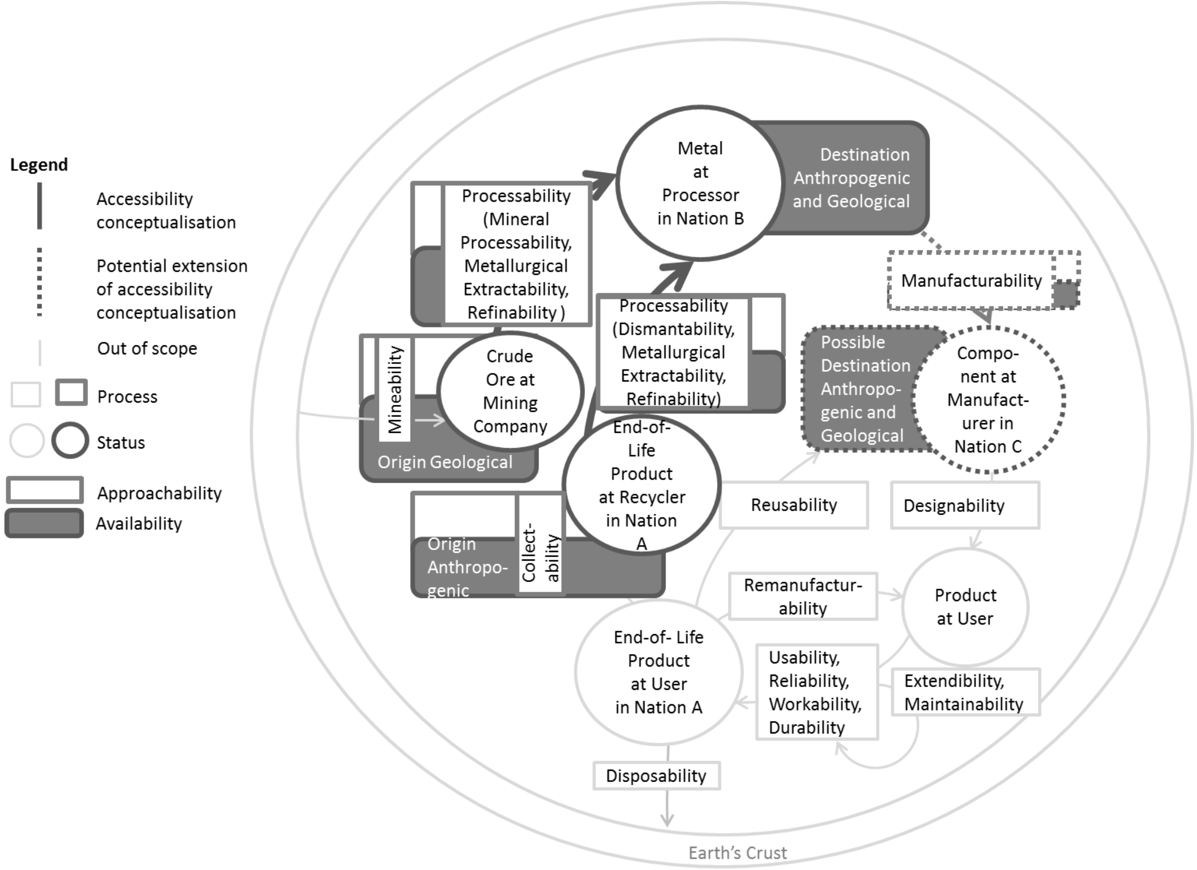

Figure 16: Positioning this conceptualisation of raw material 'accessibility' in the cycle of a material. This includes both mining anthropogenic and geological deposits.

5.6.2.1.1. Conceptual framework

'Accessibility' was part of 'availability' and 'approachability', which were respectively classified as 'low', 'moderate', or 'high', (Figure 17). 'Availability' is based on 'geological knowledge' and 'eligibility' whilst 'approachability' is built on 'technology', 'economy', 'environment' and 'society'. At this point in time, it is assumed that the components are equally weighted; this assumption during future research activities will be tested. Note that the uncertainty of the component evaluation is described as a precursor to a detailed future assessment.

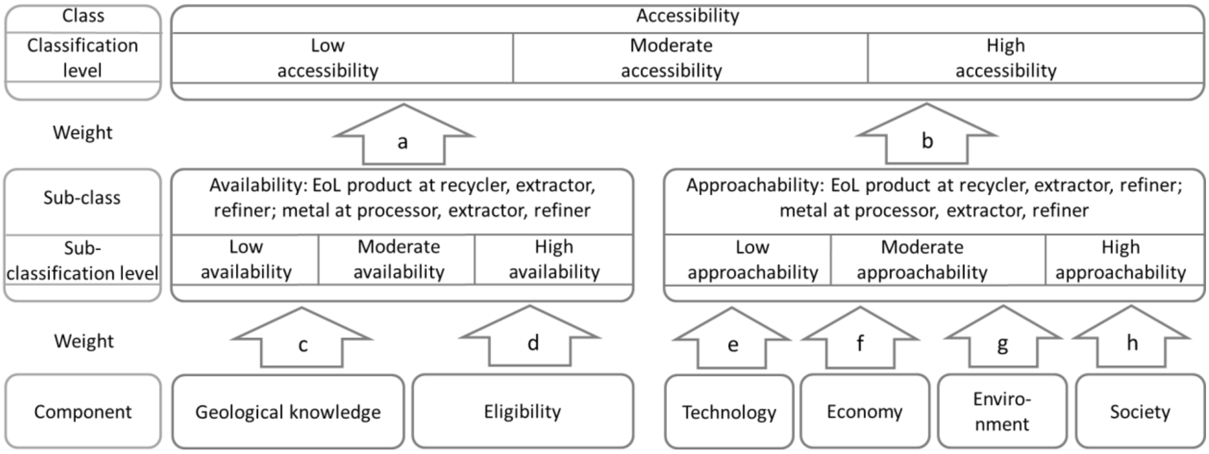

Figure 17: Evaluation framework for raw material accessibility with its sub-classes, and its constituent components, developed for an early project stage evaluation of a national or corporate level but also the common evaluation between mining deposits in the anthroposphere and geosphere as well as processing, where a-h are to be verified.

Table 14: Criteria and description of the evaluation of raw material accessibility.

	Criteria	Description		
Class	**Accessibility**	'Getting to' the material of interest for potential treatment or production by means of fully meeting the components for availability: 'geological knowledge' and 'eligibility'; as well approachability: 'technology', 'economy' and 'social' and 'environmental' impacts.		
	Classification level	**High accessibility** No 'significant' restrictions to 'accessibility'	**Moderate accessibility** Moderate restrictions to 'accessibility'	**Low accessibility** 'Significant' restrictions to 'accessibility'
Sub-class	**Availability: EoL product at recycler / crude ore at mining company and metal at processor**	'Original location and existing destination with opportunities' in the geosphere and/or anthroposphere at 'relevant' condition by means of processable amount with associated location that can be estimated with a high level of confidence (UNFC, 2010) and transparent ownership and policy enforcement.		

Component	**i) Geological knowledge**	Average processable amount at original location to be produced per year today and in foreseeable future and level of confidence (UNFC, 2010).		
	ii) Eligibility	Description of the ownership and determination of enforcement of policies and regulatory requirements.		
	Sub-classification level availability	**High availability** No ’significant’ restrictions to ‘availability’	**Moderate availability** Moderate restrictions to ‘availability’, which are processable amounts of EoL products or the Earth’s crust at associated location that can be estimated with moderate level of confidence; and raw material stream does not yet flow. Transparent ownership and policy enforcement.	**Low availability** ’Significant’ restrictions to ‘availability’ with sufficient quantity to be processed of EoL products or the Earth’s crust at associated locations that can be estimated with low level of confidence and estimated quantity of potential deposits based mainly on indirect evidence; and no transparent ownership and policy enforcement.
Sub-class	**Approachability: Collection/ mining and processing**	‘Getting’ to the material of interest with ease by means of fully operating technology. This includes collection/ mining and processing “has been confirmed to be economically viable” (UNFC, 2010); no adverse impacts on society and environment.		
Component	**i) Technology**	The status of infrastructural and technological application during collection/ mining and processing.		

	ii) Economy	The economic viability determination during collection/ mining and processing (UNFC, 2010) today and in the foreseeable future.		
	iii) Society	The social impact monitoring and prevention description and determination of selected indicators during collection/ mining and processing.		
	iv) Environment	The ecological impact monitoring and prevention and determination of selected indicators during collection/ mining and processing.		
	Sub-classification level approachability	**High approachability** No ’significant’ restrictions to ‘approachability’	**Moderate approachability** Moderate restrictions to ‘approachability’, in which infrastructure / technology is in the testing and scale-up phase in order to obtain the material of interest, which “is expected to become economically viable in the foreseeable future." (UNFC, 2010). No adverse impacts on society and environment.	**Low approachability** ’significant’ restrictions to ‘approachability’, in which infrastructure / technology is not developed yet and the material of interest “is not expected to become economically viable in the foreseeable future." (UNFC, 2010), adverse impacts on society and environment.

5.6 Evaluation of raw material accessibility

The results of the evaluation of raw material accessibility are shown in Figure 18 in the form of an aggregated evaluation grid. This grid shows that the Mt. Weld deposit results in moderate to high accessibility, due to high availability and moderate to high approachability. The EoL phosphor of fluorescent lamps with Eu in Switzerland shows moderate accessibility, i.e. high availability but moderate approachability. The other two case studies, EoL drive motor of electric car with Nd in Switzerland and EoL fibre optic cable with Er in Switzerland, were found to have low accessibility.

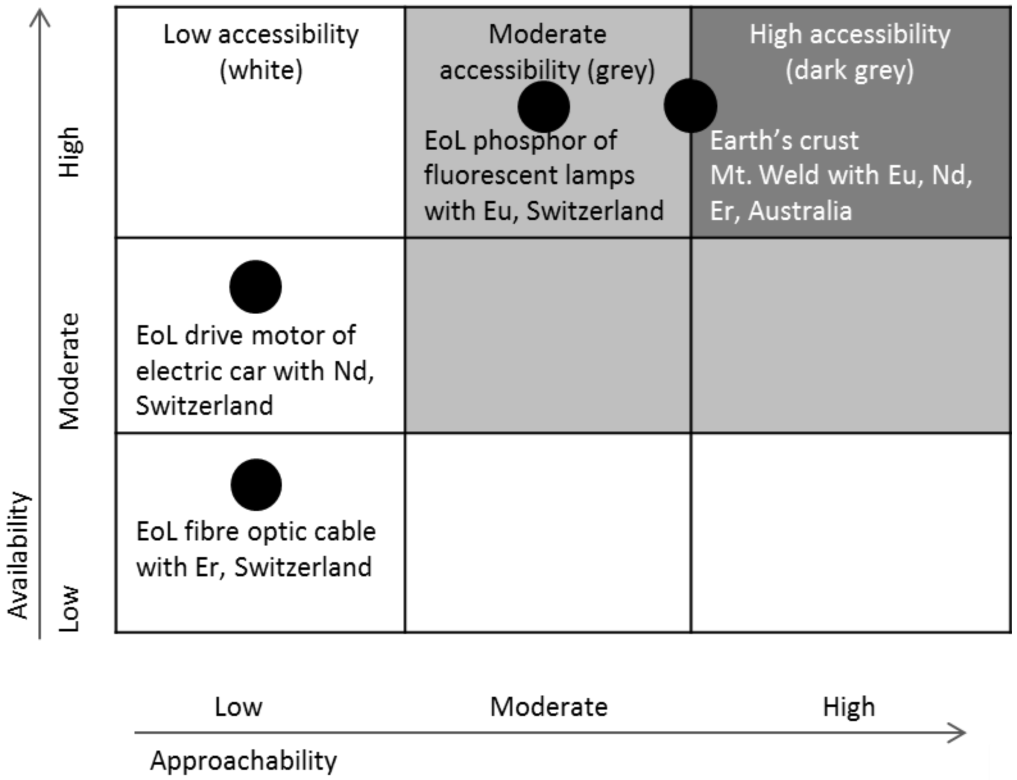

Figure 18: Proposed raw material accessibility evaluation grid of current and future 'accessibility' with selected EoL products and the Earth's crust. The black dots show the position of each deposit considered. The aggregation of 'high accessibility' is denoted in dark grey, 'moderate accessibility' in grey and 'low accessibility' in white.

The results of evaluating the application of the framework are presented in Table 15. All deposits considered in this instance resulted in quantifiable 'geological knowledge'. The deposits fluorescent lamps with Eu, Switzerland and REE deposit, Mt. Weld, Australia contain hazardous and radioactive substances. All deposits showed clear 'eligibility' apart from deposit fibre optic cable, which resulted with several potential ownerships. Hence, this deposit was classified as low availability. The approachability evaluation demonstrated various approachability levels. The REE deposit, Mt. Weld, Australia showed moderate to high approachability, because of its associated and potentially high impacts on society and environment. The deposit fluorescent lamps with Eu, Switzerland showed moderate availability, due to ‘technology’ and ‘society’. The deposit drive motor in an electric car with Nd, and fibre optic cable with Er, Switzerland showed low availability, because of both barriers in ‘technology’ and ‘economy’.

Figure 19 provides an overview of ‘accessibility’ along the operation steps: collection/ mining and processing. In particular, it illustrates, whether the operation steps are established, in up-scale development and market launching phase, under basic development, or not developed.

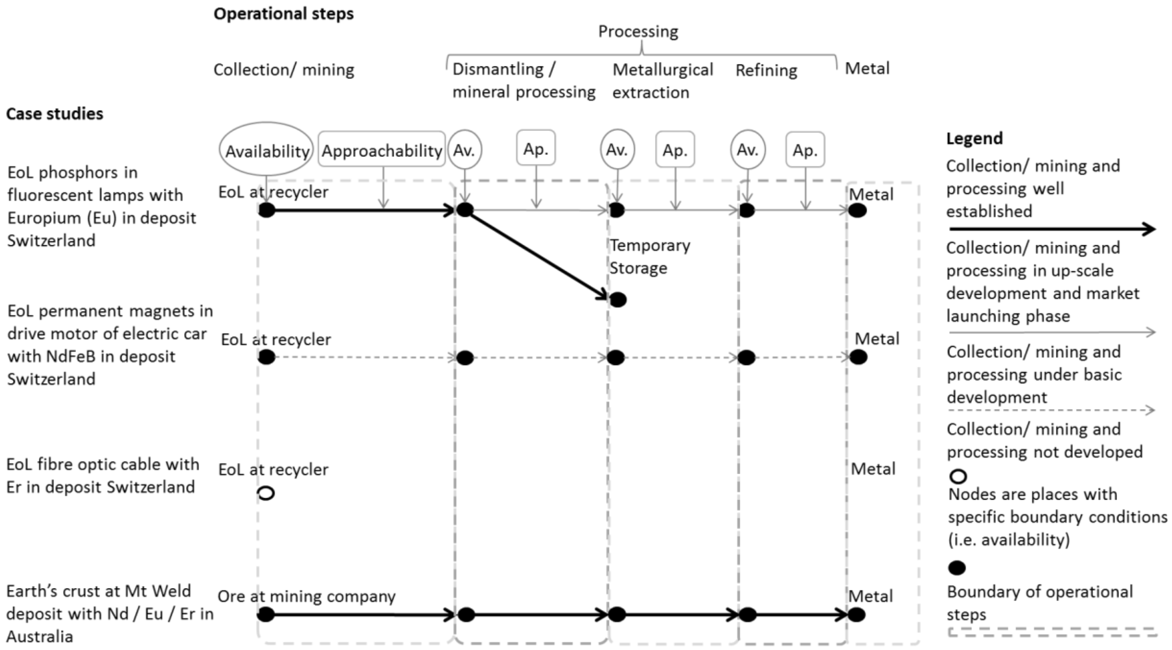

Figure 19: Visualisation of the raw material ‘accessibility’ investigations of the collection/ mining and processing and the four deposit case studies. Accessibility is considered at each operation step and provides an overview of whether the accessibility to a raw material from collection or mining is well established, in up-scale development, under basic development or not yet considered. ‘Av.’ indicates availability; ‘Ap.’ indicates approachability.

Table 15: Investigation of the current raw material accessibility status of anthropogenic and geological deposits.

EoL phosphors in fluorescent lamps with Europium (Eu) in deposit 'Switzerland'	
Availability:	• **Geological knowledge**: Available quantity of almost 1,169t lamps in 2014 (Huber and Schaller, 2015) with a mass fraction of up to 0.012 weight-% Eu per lamp (Schüler *et al.*, 2011). The quantities are systematically and longitudinally monitored by a foundation for light recycling Switzerland (Huber and Schaller, 2015). This leads to high level of confidence. • **Eligibility**: The WGI, RL is 98%, which means abiding by the quality of contract enforcement, property rights, and the courts (World Bank, 2016). During collection the owner is either the producer or the responsible organisation. In the subsequent processing, the treatment operator becomes the owner of the materials (FOEN, 2005). • **Sub-classification level**: high availability.
Approachability:	• **Technology**: With current technologies the collection rate of fluorescent lamps was 83% in 2014 (BAFU, 2012a, 2015a; Huber and Schaller, 2015). Similarly, a yield of 80% is estimated by means of solvent extraction, with development potential for demonstrating a recovery yield of 98-99% (Machacek *et al.*, 2015). The recycling implementation of phosphors remains uncommon (Turner, Williams and Kemp, 2015); the lamp powder is disposed underground with option for retrieval (Huber and Schaller, 2013). In 2014 a test batch was sent to Solvay for assessment (Swico / SENS / SLRS, 2015). • **Economy**: The costs for collection and recycling account for 0.15 to 2 Euro (EUR) per kg for up to 80% REE recovery rate; and USD 6 per kg for extraction from mercury phosphor dust (Machacek *et al.*, 2015). Low profitability of a processing plant lead to their closure at by the end of 2016 (Guenard, 2016). • **Society**: Processing was possible (December 2016) in France (Guenard, 2016), consequently, these parameters are used for this evaluation. There is moderate to little impact on society from processability. This can be exemplified by the WGI, PV 57% which means moderately politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards (Ali, 2014).

	• **Environment**: (Simoni *et al.*, 2015) reported that the greenhouse gas emissions for recycling any fluorescent lamps were about 23.5kg CO_2eq./kg for rare earth oxides (REO) and the life cycle impacts were about 32,576 UBP/kg REO. The lamp powder contains mercury (Richter and Koppejan, 2015). The implementation of stringent safety standards ensure, there will be little human health impacts (Ali, 2014). 2. **Sub-classification level**: Moderate approachability (due to ‘technology’ and ‘society’).
EoL permanent magnets in drive motor of electric car with Neodymium-Iron-Boron ($Nd_2Fe_{14}B$) in deposit ‘Switzerland’	
Availability:	• **Geological knowledge**: The average available weight is estimated 1.6t in 1 million electric cars in 2017 in Switzerland with a share of 2 weight-% Nd. The available weight is estimated, which leads to low level of confidence. • **Eligibility**: The WGI, RL is 98%, which means abiding by the quality of contract enforcement, property rights, and the courts (World Bank, 2016). The ownership is transparent, namely the recycler and metal processors. • **Sub-classification level**: Moderate availability (due to the current barrier in ‘geological knowledge’).
Approachability:	• **Technology**: The collection system for vehicles is well established in Switzerland (Widmer *et al.*, 2015). Consequently, the annual average collection is 100%. Note, that the 100% excludes export to developing countries, whereby the material is used again (Althaus and Gauch, 2010). Recycling techniques are currently under investigation (Elwert *et al.*, 2015). • **Economy**: Dismantling and processing is expected to become economically feasible in the medium or long-term future (Elwert *et al.*, 2015). • **Society**: Apart from shredding of vehicles in Switzerland, the processing is currently carried out. There is little impact on society from processability in Switzerland. This can be exemplified by the WGI, PV of 95%, highly politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards (Swico / SENS / SLRS, 2015). • **Environment:** (Elwert *et al.*, 2015) reported that there was little impact on

	the environment with global warming potential from recycling: about 14kg CO_2eq./Nd-oxide based on mass allocation. There are no hazardous and radioactive substances related to the permanent magnets in drive motors (Haan, Zah and Althaus, 2013). • **Sub-classification level**: Low approachability (due to the current barriers in 'technology' and 'economy').
EoL fibre optic cable with Erbium (Er) in deposit 'Switzerland'	
Availability:	• **Geological knowledge**: Available quantities with a total of 15,551t (Müller *et al.*, 2013) with 0.01 weight-% Er (Hering, 2006). The available weight is estimated with little information on the precise location. This bases mainly on indirect evidence. • **Eligibility**: The WGI, RL is 98%, which means abiding by the quality of contract enforcement, property rights, and the courts (World Bank, 2016). The ownership of construction and maintenance are both nationally licenced private telecom companies and municipalities (BAKOM, 2015b, 2015a), which is not transparent. At present, it seems no efforts are undertaken to change this. • **Sub-classification level**: Low availability (due to current barriers in 'geological knowledge' and 'eligibility').
Approachability:	• **Technology:** No recycling infrastructure exists or is in planning. Consequently, the recycling technologies are also not under development (Angerer, 2009b). • **Economy:** Collection, dismantling and processing is not expected to become economically viable in the foreseeable future (Angerer, 2009b). • **Society**: Collection and processing are currently not carried out but the material is hosted in Switzerland. At present there is little impact on society in Switzerland. This can be exemplified by the corruption perception index of 95%, meaning highly politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards (Swico / SENS / SLRS, 2015). • **Environment:** (Stocker, 2014) reported that the global warming potential was about 0.2 kg CO_2eq./m cable. There are no hazardous and radioactive substances related to the fibre optic cable.

	• **Sub-classification level**: Low approachability (due to the current barriers in 'technology' and 'economy').
Earth's crust deposit at Mt Weld with Nd / Eu / Er in 'Australia'	
Availability:	• **Geological knowledge**: Available quantity of 3,133t REO in 2015 (Lynas, 2015, 2015) and total estimated deposit mass in the central lanthanide of 9.88Mt with a mass fraction of 10.7 weight-% REO, 0.85 weight-% Nd, 0.02 weight-% Eu, 0.001 weight-% Er (Hoatson, Jaireth and Miezitis, 2011). Mining commenced in 2011, which means there is high level of confidence. • **Eligibility:** Mining is carried out in Australia and processing in Malaysia; consequently, both countries parameters' are used for this evaluation. The WGI, RL is, 94% for Australia and 71% for Malaysia. This shows the quality of contract enforcement, property rights, and the courts are abided (World Bank, 2016). The ownership is transparent at Lynas Corporation Limited (Machacek and Fold, 2014). • **Sub-classification level**: High availability.
Approachability:	• **Technology**: Infrastructure, mining and processing technology has commenced operating in 2012 (Schmidt, 2013; Machacek and Fold, 2014). With the current technologies a yield of 90 - 95% is achieved by means of solvent extraction (Peiró and Méndez, 2013). • **Economy**: The value of concentrate is about United States Dollar (USD) 28 per kg (Machacek *et al.*, 2015). • **Society**: There is moderate impact on society from processability. This can be exemplified by the WGI, PV 77% for Australia, which means highly politically stable and absence of violence/terrorism; and 55% for Malaysia, which means moderately politically stable and absence of violence/terrorism (World Bank, 2016) and the implementation of stringent monitoring system and safety standards during operation (Schmidt, 2013). Consequently, there is moderate impact on society. • **Environment**: (Simoni *et al.*, 2015) reported that the combined global warming potential of general mining and processing activities were about 55.7kg CO_2eq./kg REO and the life cycle impacts were recycling about 59,142 UBP/kg. This deposit is associated with radioactive thorium and

uranium (Hoatson, Jaireth and Miezitis, 2011). Regarding impact prevention, the potential emissions to water and air are carefully monitored during processing, which concentrates radioactive uranium and thorium. However, a site for long-term storage has still to be established (Schmidt, 2013).

- **Sub-classification level**: Moderate to high approachability (moderate approachability in 'environment' and 'society'.)

5.7 Discussion

5.7.1 Extraction of conceptual framework

Raw material 'approachability' has not previously been explicitly addressed at a system level. The text analysis suggests that 'accessibility' and 'availability' are not yet established terms in the literature. Only Tiess (2011) was found to distinguish clearly between accessibility to, and availability of, minerals in the context of exploration and policy development. The statistical analysis shows that for the EC corpus, the conceptualisation in urban planning has a high occurrence of the word accessibility, whereas in the MA and MG, accessibility occurs less frequently. This clearly indicates the words were distributed as Zipf's law predicted (Li, 1992). The semantic analysis of the EC corpus revealed that accessibility was strongly collocated to 'measure' and 'indicator', which indicates that an evaluation should include indicators and be measureable.

The conceptualisation of accessibility played a major role in urban planning research (Klaesson, Larsson and Norman, 2015). This urban planning conceptualisation dates back to work undertaken by Hansen (1959) (Karlsson and Gråsjö, 2013), are widely applied, and is based on the physical law of gravitation (Klaesson, Larsson and Norman, 2015). However, the integration of different interdependencies for 'availability' and 'approachability' may lead to ambiguity in the definition and quantification of 'accessibility' (Janelle and Hodge, 2013), especially since they have been described as an unclear notion with numerous definitions and conceptualisations (Curl, Nelson and Anable, 2011; Karlsson and Gråsjö, 2013). To overcome this problem, this conceptualisation was developed following evaluations in urban planning, the UNFC classification framework, and material criticality assessments (Graedel *et al.*, 2012; EC, 2014; Tuma *et al.*, 2014).

The evaluation framework proposed in this study (Figure 17) contributes to other raw material classifications, such as UNFC (UNFC, 2010) or CRIRSCO (CRIRSCO, 2013), in that it addresses raw material approachability at a system level. Furthermore, this framework considers the 'eligibility' of raw materials for extraction, a component not explicitly included in other raw material classifications. Considering 'eligibility', this is essential for raw material assessments, as without clear 'eligibility' (inter alia legal permission to mine/processing), raw materials cannot be accessed. This approach explicitly evaluates the influence of technology, which is reportedly the most important consideration for effective recycling (Hagelüken, 2014) and mining (Tilton, 2002). To ensure long-term raw material accessibility, it is also essential to consider the sustainability aspects: society, environment, and economy (Corder, McLellan and Green, 2010). For this framework, the different components and their indicators were addressed by means of expert's survey with a Delphi study in Chapter 6. The framework further differs from alterative evaluations as it aims to facilitate early project stage evaluation with limited availability of robust data (Roelich *et al.*, 2014) and which often involves high uncertainty (Weber, 2013). This use of three categories ('low', 'medium', 'high') does reflect the lack of data (sections G.10 and G.11). Similarly to this framework, the UNFC comprises three to four categories. However, in contrast, this framework comprises one main category ('accessibility'), two sub-classes ('availability' and 'approachability'), and six components (namely 'geological knowledge', 'eligibility', 'technology', 'economy', 'society' and 'environment'). Additionally, this framework provides an indication about the current supply situation rather than a detailed assessment. This indication could particularly support the prospection phase, which aims to develop knowledge on type, location, volume, legislation, technology and costs (Winterstetter *et al.*, 2016b). The insights gained from the application of this framework could provide important information to support a UNFC classification. Hence, the availability component 'geological knowledge' could provide basic knowledge for the UNFC category G (also known as geological knowledge). The approachability component 'technology' could provide basic knowledge on the existing technology and infrastructure, which are needed in the category F (field project status and feasibility). The availability component 'eligibility' and the approachability components 'economy', 'society' and 'environment' could deliver fundamental information, as this is required in the category E (economic and social viability).

5.7.2 Evaluation of raw material accessibility

The application of this developed evaluative framework to the case studies has shown that it is possible to describe and quantify the components of 'accessibility': 'availability', and 'approachability' of different anthropogenic and geological raw material deposits (Figure 18). Perhaps unexpectedly, the currently mined Mt. Weld deposit generates an 'approachability' outcome of medium to high, because the quantified societal and environmental impacts associated with processing in Malaysia require the same level as European standards. The evaluations show that it is possible to compare the mining of deposits from EoL products with mining the Earth's crust. This could potentially be applied to any EoL products and mine from the Earth's crust. This evaluation could be extended to cover multiple metals per product or deposit. Multiple metals per products were evaluated by means of obsolete personal computers and Neodymium Iron Boron permanent magnets (Winterstetter *et al.,* 2016b). Multiple metals per deposit were evaluated by a landfill (Winterstetter *et al.,* 2016b) and Vienna's subway network (Lederer *et al.*, 2016). There are two constraints on this aggregated evaluation, namely that the different components are not apparent and that the current evaluation is static.

The investigation of the accessibility components demonstrates that it is possible to underpin this evaluation with numerical statements (Table 15). Nevertheless, the selection of each indicator requires expert justification (Tuma *et al.,* 2014). This quantification of the operational steps: collection/ mining and processing could be expanded with a more detailed investigation of each step.

Quantitative characterisation and evaluation of the availability component 'geological knowledge' demonstrated that the mass fractions of raw material in anthropogenic deposits are higher than those of the geological deposits (Table 15). However, its quantification is influenced by the limited availability of relevant data and assessment of associated uncertainty, particularly with respect to the very low concentration of REEs (Simoni *et al.*, 2015). This quantification could be expanded with a calculation on the energy use as implemented by Peiró and Méndez (2013).

The evaluation of the availability component 'eligibility' revealed that with unclear and restricted ownership (such as was the case for fibre optical cable), accessibility to raw materials becomes difficult (Table 15). This can be exemplified by China's ownership of 63% of the world market for REE and their intentions to buy REE mines in Australia and Greenland (Sprecher *et al.* 2015). However, quantification of material 'eligibility' proved demanding, with most existing data being descriptive rather than quantitative. Consequently, here 'eligibility' was quantified with the rule of law indicator from the WGI project (World Bank, 2016) and then described. For future research, alternative approaches should also be considered, which may include the Policy Potential Index (PPI) or, the Herfindahl-Hirschman Index (HHI). The PPI is used to provide governments with a report card on how attractive their policies are from an exploration manager's point of view (Graedel *et al.*, 2012) and includes issues concerning mining permissions. The PPI provides information on the mining at system level but does not explicitly account for the influence of ownership of mining companies to the government or society. However, to understand the worldwide restrictions better, the HHI provides information on the concentration ratio of metal producing companies or countries in a bigger geographical area, i.e. country or world. (Gleich *et al.*, 2013), yet lacks on information about a single company. Given that ownership was identified as a central criterion for 'eligibility' in this study (Table 15) it is important that an appropriate indicator is determined to quantify this facet.

Following the quantification of the component 'technology', I found that only limited information is available to quantify the recovery rate for the different processes with a high degree of certainty (Table 15). An alternative approach may be the technology readiness assessment (Winterstetter *et al.,* 2015), which is commonly applied in the oil and gas industry to rank the establishment of a technology on a scale of 1 (low) to 9 (high) (Strutt, Roberts-Haritonov and Woods, 2009). However, no efforts have been undertaken to implement this in the non-energy extractive industry.

The results for the 'economy' component evaluation revealed that there is a dearth of information concerning the costs of mining either the anthroposphere or the geosphere (Table 15). For instance, the recovery of EoL permanent magnets from drive motors is in its infancy; consequently, no price could be established. Nevertheless, a prediction of economic viability was possible. For deposits in the Earth's crust, price data with the lowest uncertainty were available from the metal trading price index. The quantitative evaluative approach of this component requires further investigation.

The impacts on 'society' were worse in the case of mining deposits in the geosphere than the anthroposphere (Table 15). Impact quantification was based on a single indicator, the politically stability and absence of violence/terrorism from the WGI project (World Bank, 2016). This approach potentially limits the overall statement of the impacts on the society. However, there are only a few other indicators at system level that may be applied, namely control of corruption, risk of child labour and freedom of speech (Tuma *et al.*, 2014). It is being verified to expand this system level statement with indicators, such as hours of work or occupational injuries (Dewulf *et al.*, 2015) to provide a more comprehensive statement on social impacts. In contrast to Graedel *et al.* (2012), the use of the human development index was rejected in the present study, as it was concluded that quantification of health, education and income of a country is not sufficiently specific for an industry processing in a country.

These results show that, in the cases examined, the negative impacts on the 'environment' from geological mining (based on global warming potential only) are considerably higher than those for anthropogenic mining (Table 15). Environmental impact was assessed in the present study based solely on potential global warming impacts. This approach represents a limitation of this methodological framework as such a singular focus does not address the wide range of potential environmental impacts that may be caused by raw materials mining and production activities (e.g. freshwater acidification, ecotoxicity, etc.). However, such an approach is considered justified and appropriate for an early project stage evaluation. Further, since there is limited data availability for many metals, with more data available on global warming potential, this becomes an important environmental impact category (Nuss and Eckelman, 2014). For the quantification of this important impact category, a clear choice of system boundary, location and energy mix are central, as these can make a significant difference on the final result (Laner *et al.*, 2016). Additionally, as a complementation, measures for impact monitoring prevention were described (Table 15).

Finally, this use of a one-directional graph at different operation steps (Figure 19) enables easy comparison of the availability and approachability of raw material in EoL products or the Earth's crust along operation steps and provides a simple representation of reality. This approach in turn elucidates potential collection/ mining and processing disruption, which is currently lacking (Roelich *et al.*, 2014). This graphical interpretation could be further developed with the bipartite graph from e.g. Pauliuk et al.'s (2015) accounting framework to model the socio-economic situation in detail.

5.8 Conclusion and outlook

Availability is commonly used in raw material supply evaluations, whilst other researchers suggest that raw material supply should be evaluated based on accessibility. This difference has led to semantic confusion within the field of raw material supply. Based on the quantitative linguistic approach, it was concluded that raw material supply evaluation can be evaluated based on the accessibility of materials, 'accessibility' comprising: availability and approachability. However, whilst raw material availability is commonly addressed in previous studies, raw material 'approachability' has not yet been explicitly evaluated at a system level. Consideration of this aspect is essential to gain a thorough understanding of the accessibility of raw materials. To address this, the urban planning framework was the basis for this conceptual framework for raw material 'accessibility' evaluation. This proposed framework comprises an assessment of raw material 'availability', for which the components 'geological knowledge' and 'eligibility' are considered; and 'approachability', for which the components 'technology', 'economy', 'society', and 'environment' are considered. The framework was applied to evaluate the raw material accessibility of four different REE deposits. The results demonstrate the potential of this framework tool, as an early stage assessment for projects mining deposits in the anthroposphere and geosphere. Possible next steps include further differentiation and quantification of the criteria and querying with a large number of experts, which is addressed in Chapter 6.

Chapter 6 Evaluating the accessibility of raw metals from end-of-life products and the Earth's crust under sustainability considerations: methodological framework refinement, confirmation, consolidation and application

6.1 Linkage of chapter with PhD research

This chapter attempts to bridge the knowledge gap concerning the lack of an interdisciplinary methodological framework for characterising and evaluating the accessibility of raw materials. This not only includes sustainability considerations but also potential impacts on technological, economic and regulatory aspects (Velis and Brunner, 2013; Hagelüken, 2014). Based on a systematic review of existing quantitative approaches for evaluating raw material accessibility (section 2.3) and extracted concepts presented in Chapter 6, a refinement and confirmation of sub-components and indicators by experts is presented. Then, the framework is consolidated. This will be underpinned by a characterisation and evaluation of four case studies, which will show the utility of the framework. For consistency, this chapter is structured similarly to Chapter 5. This chapter consists of the development of the methodological framework, and subsequent application. This is also the structure of the intended publication in the Journal of Cleaner Production as two papers. It is prepared as a manuscript, however, for clarity, other thesis chapters are included and are referenced.

6.2 Graphical abstract

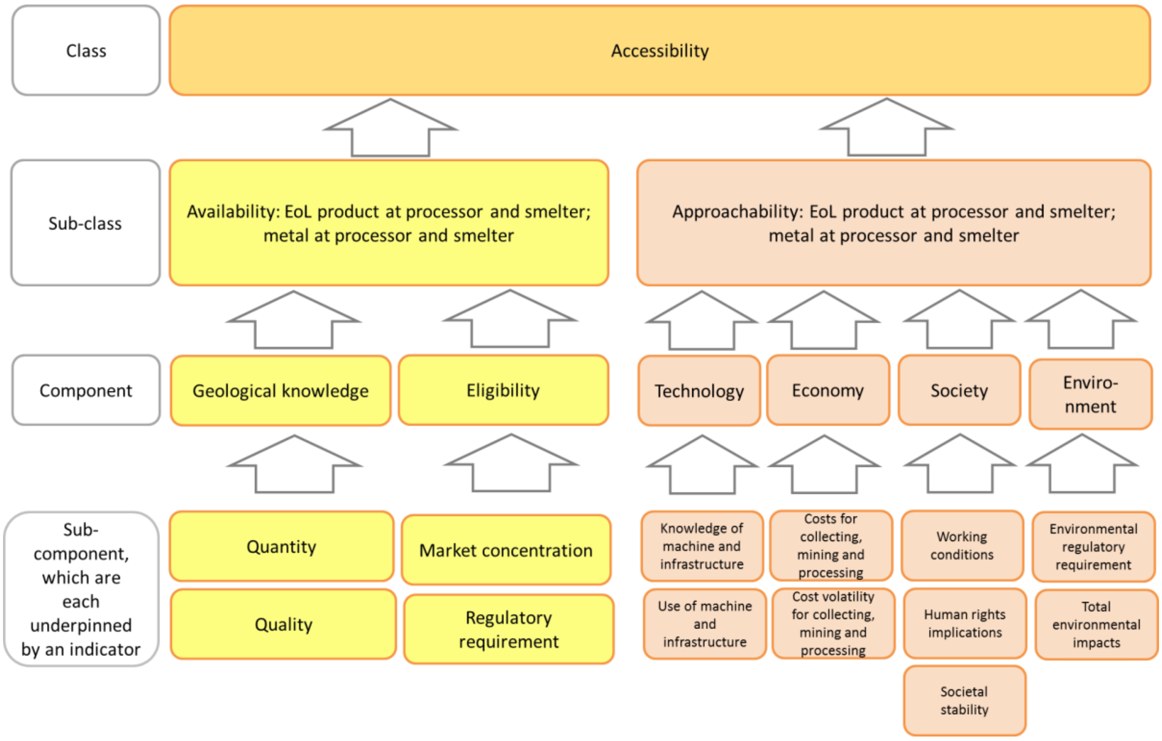

Figure 20: Graphical abstract of research in Chapter 6.

6.3 Introduction

Over the past 40 years, the number of metallic elements being used in electronic products has drastically increased. For example, 11 different elements were used in printed circuit boards (PCB) in 1980, whilst 45 elements were used by the year 2000. Furthermore, as the use of electronic products increases across society, the amount of electronic products requiring end of life (EoL) management also increases. In Switzerland, for instance, approximately 150,000 desktop computers and 160,000 laptops, which include PCBs and hard drive disks (HDD) with permanent magnets, were collected at e-waste facilities in 2015 (Thiébaud *et al.*, 2016). Hence, there is not only a greater amount of metals that are being discarded each year, but also a greater variety (Johnson *et al.,* 2007). Nevertheless, 34 metals still have recycling rates of less than 1% (UNEP, 2011). To tackle this problem, methods are needed to effectively recover technologically-important metals from EoL products (Hagelüken, 2014).

Metals can be extracted from the Earth's crust. Whilst deposits are distributed globally, many metals are concentrated in just a few countries (Wall, 2014). For example, the scarcely-concentrated rare earth elements (REE) are produced in only five countries (Simoni, 2012), with China accounting for 95% of the world production in 2010 to 2014 (EC, 2017b). This dependency, in conjunction with the Chinese export restriction in 2010 (estimated to be 40% of production), triggered panic buying of REE by a Japanese company in 2010 that led to a global REE supply crisis (Sprecher *et al.*, 2015). Additionally, their mining and processing has led to increased concern regarding social and environmental compliance and impacts (Ali, 2014; Klinger, 2015; Bach *et al.*, 2017). These examples highlight how the availability of raw materials can be uncertain and the maintenance of sustainable supply has become increasingly important to industry.

To better understand this situation, a number of methods for evaluating material availability have been developed (Spiers, Houari and Gross, 2013), including the EU criticality evaluation (Moss *et al.*, 2013) and the metal criticality determination developed by Graedel *et al.* (2012). Such information can help industrial actors or policy makers better understand the criticality of key raw materials (Bedder, 2015). A multi-commodity assessment investigates material availability in different contexts, such as different technologies (Moss *et al.*, 2013), sectors (USDOE, 2011), or geographies (NRC, 2008). Common among these approaches is the application of a wide range of performance indicators[24] and composite indicators[25], with which results are aggregated over the entire supply chain (Bedder, 2015). Other evaluation approaches comprise a globally-harmonised metal resource availa-

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[24] Statistical measures that are used to consolidate complex data into a simple number or rank that is meaningful to policy makers and the public (Merry, 2011).

[25] A composite indicator includes the compilation of individual indicators into a single index, on the basis of an underlying model of a measured multi-dimensional concept (adopted from OECD, 2013).

bility assessment, *The United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009* has been developed by the UNFC (UNFC, 2010). Specifications thereof are currently being developed for anthropogenic resources (Heuss-Aßbichler *et al.*, 2017). The purpose of these generic frameworks is to establish comparability between different types of raw materials on a (semi-) quantitative basis. They have also been used to evaluate anthropogenic metal resources from landfills and EoL products (Winterstetter *et al.*, 2015). To provide a comparable statement on different types of raw materials, the UNFC framework does not suggest the use of specific indicators. The UNFC is currently advancing to include sustainability considerations on society and environment (UNFC, 2017a, b, d). The UNFC classification framework consists of the class, sub-classes and three to four categories that are distinguished by different category types, namely: economic and social viability, field project status and feasibility, and geological knowledge (UNFC, 2010). None of these availability[26] evaluations consider approachability[27]. The concepts of availability and approachability can be linked in the concept of raw material accessibility. To support this research need, 16 existing availability approaches were reviewed regarding potential framework elements, see Chapter 2, section 2.3.3.

An initial framework was developed and applied (Chapter 5). This initial framework aimed to rethink raw material management and establish a consistent use of accessibility and related terms. However, there remains a lack of refinement and confirmation of the developed and initially applied method, namely ‘accessibility evaluation framework’. Additionally, there is a need to introduce am additional level below the components with sub-components[28] to cover a broader understanding of ‘geological knowledge’, ‘eligibility’, ‘technology’, ‘economy’, ‘society’ and ‘environment’. These sub-components should then be underpinned by one indicator each. If there is more than one indicator for a sub-component, the framework needs to be refined and confirmed.

There is a need to advance the management of raw materials at different levels:

(i) To improve the understanding of a raw material’s accessibility (Chapter 5);

(ii) To understand the different operational steps in the supply chain of scarce metals from a broad perspective (i.e. based on a wide variety of sustainability indicators) to highlight potential bottlenecks and identify potential areas for improvement (Sprecher *et al.*, 2015), such as in determining the difference between developing and developed countries (Ali, 2014); and

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[26] The quality of being at hand when needed (Mueller *et al.*, 2017)

[27] The attribute of being easy to meet or deal with (Mueller *et al.*, 2017)

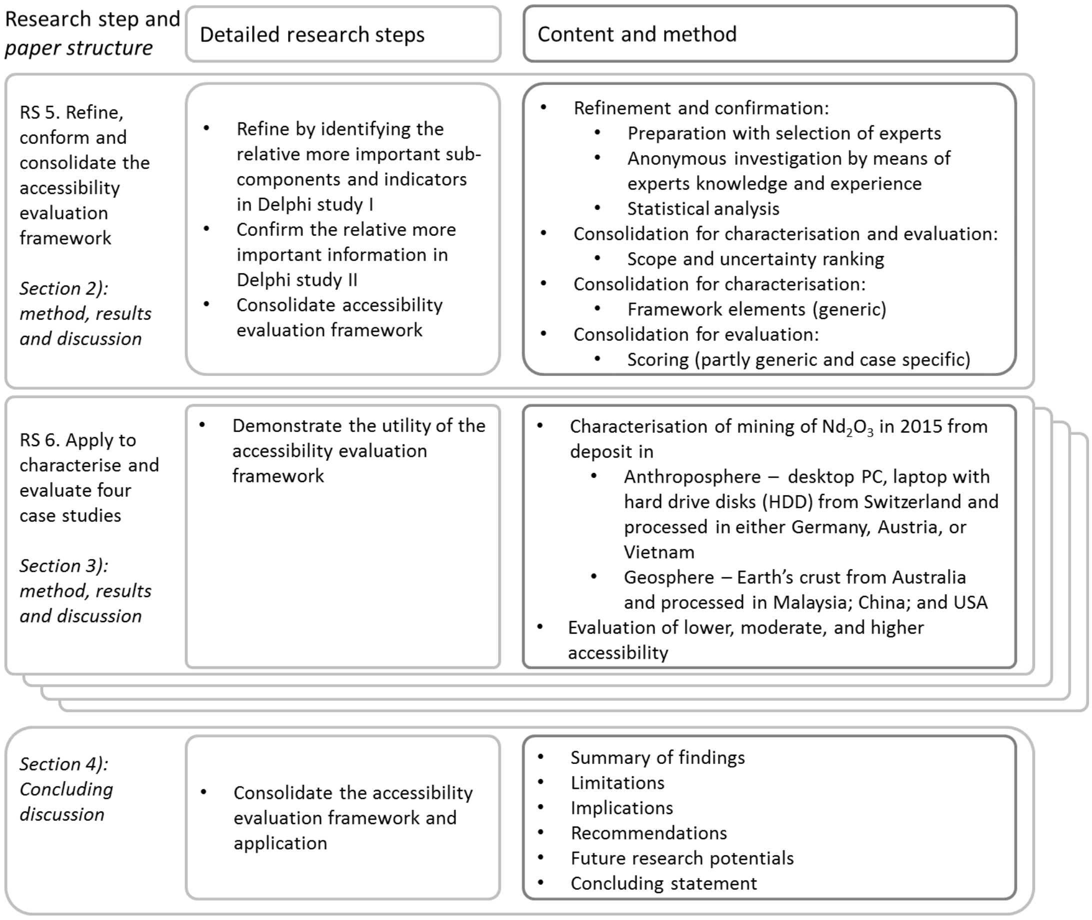
[28] The sub-part that combines with other parts to a component (adopted from Cambridge English Dictionary, 2016a).

(iii) To consistently characterise and evaluate the management of raw materials that is in-line with existing methods (e.g. the UNFC or criticality evaluations).

This Chapter aims to advance the initially developed framework and apply a (semi-) quantitative methodological framework for characterising and evaluating the accessibility of scarce metals from EoL products and the Earth's crust at an early-project development stage. The objectives were to:

(i) Refine, confirm and consolidate a consistent methodological framework by expert judgements; and
(ii) Demonstrate the utility of the advanced framework through case studies of REEs sourced from HDDs in desktop PCs and laptop deposits from Switzerland, and the Earth's crust from ore in China, Australia and the USA.

In section 2) refinement, confirmation, and consolidation of the methodological framework are included, and in section 3) subsequent application with characterisation and evaluation of raw material accessibility are included. The final section 4) consists of a concluding discussion (Figure 21).



Research step and *paper structure*	Detailed research steps	Content and method

RS 5. Refine, conform and consolidate the accessibility evaluation framework
Section 2): method, results and discussion
	• Refine by identifying the relative more important sub-components and indicators in Delphi study I
	• Confirm the relative more important information in Delphi study II
	• Consolidate accessibility evaluation framework
		• Refinement and confirmation:
		  • Preparation with selection of experts
		  • Anonymous investigation by means of experts knowledge and experience
		  • Statistical analysis
		• Consolidation for characterisation and evaluation:
		  • Scope and uncertainty ranking
		• Consolidation for characterisation:
		  • Framework elements (generic)
		• Consolidation for evaluation:
		  • Scoring (partly generic and case specific)

RS 6. Apply to characterise and evaluate four case studies
Section 3): method, results and discussion
	• Demonstrate the utility of the accessibility evaluation framework	• Characterisation of mining of Nd_2O_3 in 2015 from deposit in
		  • Anthroposphere – desktop PC, laptop with hard drive disks (HDD) from Switzerland and processed in either Germany, Austria, or Vietnam
		  • Geosphere – Earth's crust from Australia and processed in Malaysia; China; and USA
		• Evaluation of lower, moderate, and higher accessibility

Section 4): Concluding discussion	• Consolidate the accessibility evaluation framework and application	• Summary of findings • Limitations • Implications • Recommendations • Future research potentials • Concluding statement

Figure 21: Overview on thesis research steps and linking them with Chapter 6's research steps, content and method.

6.4 Framework refinement, confirmation and consolidation

6.4.1 Framework refinement and confirmation: method

A detailed description of this method can be found in section 3.4.

6.4.2 Framework refinement and confirmation: results and discussion

Through these experts, I was able to statistically justify for one component, two sub-components and one to two indicators. Expressed in numbers, this survey began with 16 sub-components, 12 indicators (Table 5); and ended with 13 sub-components and 7 indicators (Table 20). The results of the expert judgement distribution showed that most experts ranked 'very important' on the Likert scale, which is point 4 out of 5 for round I and 3 out of 4 in round II. Very few, i.e. a maximum of 5 experts per question, ranked 'not at all important', point 1 out of 5 on the Likert scale for round I. As a difference between rounds one and two, the results indicated more towards 'very important' (Table 17). This indicates consensus establishment among the experts.

The results of the statistical investigation are provided in Table 18 and Table 19. Regarding the mean values of Table 18, the results were between 3 and 5, indicating moderately important to very important.

The results of the Delphi study and statistical analysis enabled a refinement and confirmation of the sub-components and indicators. Through these, relatively more important sub-components and indicators could be established. As anticipated with this study, two to three sub-components and two to three indicators were identified for each component. This was possible in round I of the Delphi study with the exception of the component 'society' and sub-component **'regulatory requirement**'. In round II, the consolidated expert judgements confirmed the results from round I. Thereby, for the component 'society', three relatively more important sub-components were identified. For the sub-component **regulatory requirement**, one relatively more important indicator was identifiable (Table 20).

The results also showed strong consensus for the indicator **non-fatal occupational injuries** of the sub-component **working conditions**. The remainder of the results demonstrated weak to very weak consensus. Regarding the sub-components, weak consensus resulted for the sub-components of 'geological knowledge**'** and very weak consensus for the other sub-components. Regarding the indicators, weak consensus resulted from the indicators of the sub-components '**use of machine and infrastructure**'. Very weak consensus resulted for the indicators **regulatory requirement**, **societal stability**, **ecosystems** and **human health**. Overall, there is little consensus among experts. Similarly, in life cycle assessments, among the indicators relating to metallic raw materials, there is low agreement on which indicator to use in 20 years of research (Klinglmair, Sala and Brandão, 2014; Drielsma *et al.*, 2016). However, a significant difference between the results of the last two rounds was identified and in this way the Delphi survey after round II could be terminated.

The results of the expert comments showed two major findings:

- The experts suggested integrating this framework to the UNFC classification framework. This framework includes in one indicator: masses and a descriptive justification. For details see UNFC (2010).
- The experts indicated that projects are approved despite significant shortcomings towards society and the environment, particularly in poor and non-democratic governed countries.

Table 16: Overview of the investigated sub-components and (composite) indicators by means of Delphi survey I and II. Note, for each sub-component that has more than one indicator, I refined and confirmed the indicators to identify one sub-component that is underpinned by one indicator. Description of the refined and conformed, sub-components, and indicators is in Table 21. The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability.

Class	Sub-class	Component	Sub-component	Inves-tigated in Delphi survey I and II	Indicator	Inves-tigated in Delphi survey I and II
Accessibility	Availability	Geological knowledge	Quantity	X	Annual mass flow	
			Quality	X	Mass fraction	
			Mine life	X	Time	
		Eligibility	Market concentration	X	Market concentration	
			Regulatory requirement	X	WGI 'rule of law'	X
					Operating license	X
			Policy implementation	X	Policy perception	
	Approachability	Technology	Knowledge of machine and infrastructure	X	Knowledge of machine and infrastructure	
			Use of machine and infrastructure	X	Indexed annual rate of collection, mining recovery and processing recovery	X
					Cumulative energy demand	X
					Exergy replacement costs	X
		Economy	Costs for collecting, mining and processing	X	Indexed costs in a country	
			Cost volatility for collecting, mining and processing	X	Indexed cost volatility in a country	
		Society	Social regulatory requirement	X	Social regulations and standards	
			Working conditions	X	Working hours	X
					Non-fatal occupational injuries	X
			Human rights implications	X	Freedom of speech	
			Societal stability	X	Political stability	X
					Corruption perception	X
		Environment	Environmental regulatory requirement	X	Environmental regulations and standards	
			Total environmental impacts	X	Ecosystems	X
					Resource depletion	X
					Human health	X

Table 17: Results of Delphi study round I and II with experts' judgement distribution of sub-components and indicators. The order of the sub-component and indicators is alike in the resulting framework. The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability.

No	Component	Sub-component	Indicator	Distribution of expert's judgement on importance in %								
				Delphi survey I (58 experts in total)					**Delphi survey II** (48 experts in total)			
				Not at all	Not very	Moderately	Very	Extremely	Not very	Moderately	Very	Extremely
Sub-component selection												
1	Geological knowledge	Quantity		0	3	13	47	37	0	8	65	27
2		Quality		0	2	5	27	66	1	3	14	82
3		Mine life		0	8	20	46	26	4	34	51	10
4	Eligibility	Market concentration		0	3	18	40	39	0	8	60	32
5		Regulatory requirement		0	2	7	51	39	0	4	58	38
6		Policy implementation		0	5	32	46	17	0	26	56	18
7	Technology	Knowledge of machine and infrastructure		0	4	29	52	14	0	11	74	14
8		Use of machine and infrastructure		0	6	25	50	19	0	13	76	12
9	Economy	Costs for collecting, mining and processing		0	0	7	50	43	0	0	53	47
10		Costs volatility for collecting, mining and processing		0	4	15	56	25	0	14	61	25
11	Society	Social regulatory requirement		0	3	30	37	30	0	37	56	7
12		Working conditions		0	6	17	54	23	0	17	52	31
13		Human rights implications		1	6	20	45	28	1	22	48	29
14		Societal stability		0	9	18	42	31	1	20	47	32
15	Environment	Environmental regulatory requirement		0	1	13	49	38	0	3	59	38
16		Total environmental impacts		0	3	13	46	38	0	7	59	34
Indicator selection												
17	Eligibility	Regulatory requirement	WGI 'rule of law'	0	3	21	39	37	0	13	63	25
			Operating license	0	2	9	53	36	0	3	55	43
18	Technology	Use of machine and infrastructure	Indexed annual rate of collection, mining recovery and processing recovery	0	2	15	57	27	0	1	68	31
			Cumulated energy demand	1	8	27	54	10	1	15	70	15
			Exergy replacement costs	2	12	27	44	16	3	38	52	7
19	Society	Working conditions	Working hours	1	12	39	39	11	3	60	37	0
			Non-fatal occupational injuries	0	2	10	47	42	0	2	46	52
20		Societal stability	Political stability	0	0	14	45	41	0	3	62	36
			Corruption perception	0	4	31	46	19	0	18	71	12

No	Component	Sub-component	Indicator	Distribution of expert's judgement on importance in %								
				Delphi survey I (58 experts in total)					**Delphi survey II** (48 experts in total)			
				Not at all	**Not very**	**Moderately**	**Very**	**Extremely**	**Not very**	**Moderately**	**Very**	**Extremely**
21	Environment	Total environmental impacts	Ecosystems	0	1	14	46	38	1	7	58	35
			Resource depletion	3	10	18	43	26	5	16	61	19
			Human health	0	1	12	55	32	1	3	54	43

Table 18: Results of Delphi study round I and II regarding mean value and standard error of statistical analysis. The column, namely: 'statistically most significant different sub-component or indicator' links the statistical significant result of Table 19. The last column denotes the selected sub-components and indicators that were consolidated in the framework. The order of the sub-component and indicators is alike in the framework structure. The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability.

No	Component	Sub-component	Indicator	Delphi survey I		Statistically most significant different sub-component or indicator (details in Table 19)	Delphi survey II		Statistically most significant different sub-component or indicator (details in Table 19)	Selected sub-component and indicator for framework consolidation
				Mean value from Likert scale	Standard error		Mean value from Likert scale	Standard error		
Sub-component selection										
1	Geological knowledge	Quantity		3.98	0.114		4.08	0.083		X
2		Quality		4.41	0.110		4.65	0.101		X
3		Mine life		3.62	0.132	X	3.44	0.111	X	
4	Eligibility	Market concentration		3.97	0.115		4.13	0.087		X
5		Regulatory requirement		4.16	0.098		4.25	0.082		X
6		Policy implementation		3.57	0.108	X	3.77	0.095	X	
7	Technology	Knowledge of machine and infrastructure		3.57	0.110		3.94	0.075		X
8		Use of machine and infrastructure		3.59	0.121		3.90	0.074		X
9	Economy	Costs for collecting, mining and processing		4.26	0.084		4.40	0.071		X
10		Cost volatility for collecting, mining and processing		3.81	0.117		3.98	0.092		X
11	Society	Social regulatory require-		3.74	0.114		3.56	0.084	X	

No	Component	Sub-component	Indicator	Delphi survey I		Statistically most significant different sub-component or indicator (details in Table 19)	Delphi survey II		Statistically most significant different sub-component or indicator (details in Table 19)	Selected sub-component and indicator for framework consolidation
				Mean value from Likert scale	**Standard error**		**Mean value from Likert scale**	**Standard error**		
		ment								
12		Working conditions		3.72	0.117		2.98	0.101		X
13		Human rights implications		3.66	0.136		3.85	0.111		X
14		Societal stability		3.64	0.139		3.90	0.112		X
15	Environment	Environmental regulatory requirement		4.10	0.097		4.27	0.077		X
16		Total environmental impacts		4.03	0.110		4.17	0.086		X
Indicator selection										
17	Eligibility	Regulatory requirement	WGI 'rule of law'	3.91	0.116		4.00	0.089	X	
			Operating license	4.05	0.111		4.31	0.080		X
18	Technology	Use of machine and infrastructure	Indexed annual rate of collection, mining recovery and processing recovery	3.90	0.109		4.23	0.068		X
			Cumulated energy demand	3.43	0.116	X	3.85	0.089	X	
			Exergy replacement costs	3.28	0.139	X	3.42	0.102	X	

No	Component	Sub-component	Indicator	Delphi survey I		Statistically most significant different sub-component or indicator (details in Table 19)	Delphi survey II		Statistically most significant different sub-component or indicator (details in Table 19)	Selected sub-component and indicator for framework consolidation
				Mean value from Likert scale	Standard error		Mean value from Likert scale	Standard error		
19	Society	Working conditions	Working hours	3.22	0.118	X	4.21	0.079	X	
			Non-fatal occupational injuries	4.14	0.103		4.40	0.083		X
20		Societal stability	Political stability	4.16	0.095		4.25	0.076		X
			Corruption perception	3.62	0.107	X	3.83	0.081	X	
21	Environment	Total environmental impacts	Ecosystems	4.03	0.113		4.13	0.097		X
			Resource depletion	3.36	0.159	X	3.67	0.124	X	
			Human health	4.02	0.106		4.27	0.093		X

Table 19: Results of the statistical investigation of the relative more important sub-components and indicators, i.e. statistically significant difference. The order of the sub-component and indicators is alike in the concluding framework. The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability. N/A means not available.

<table>
<tr><th>No</th><th>Component</th><th>Sub-component / Indicator</th><th colspan="6">Delphi survey I (58 experts in total)</th><th colspan="6">Delphi survey II (48 experts in total)</th><th>Significant difference</th></tr>
<tr><td colspan="16">Sub-component selection</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">1 (e.g. quantity) to 2 (e.g. quality)</td><td colspan="2">1 to 3</td><td colspan="2">2 to 3</td><td colspan="2">1 to 2</td><td colspan="2">1 to 3</td><td colspan="2">2 to 3</td><td></td></tr>
<tr><td>1</td><td rowspan="3">Geological knowledge</td><td>1 Quantity</td><td colspan="2" rowspan="3">0.01</td><td colspan="2" rowspan="3">0.016</td><td colspan="2" rowspan="3">0.00</td><td colspan="2" rowspan="3">0.00</td><td colspan="2" rowspan="3">0.00</td><td colspan="2" rowspan="3">0.00</td><td rowspan="3">Significant difference between all sub-components</td></tr>
<tr><td>2</td><td>2 Quality</td></tr>
<tr><td>3</td><td>3 Mine life</td></tr>
<tr><td>4</td><td>Eligibility</td><td>1 Market concentration</td><td colspan="2" rowspan="3">0.095</td><td colspan="2" rowspan="3">0.0027</td><td colspan="2" rowspan="3">0.00</td><td colspan="2" rowspan="3">0.291</td><td colspan="2" rowspan="3">0.02</td><td colspan="2" rowspan="3">0.001</td><td rowspan="3">Significant difference between all to 3. policy implementation</td></tr>
<tr><td>5</td><td></td><td>2 Regulatory requirement</td></tr>
<tr><td>6</td><td></td><td>3 Policy implementation</td></tr>
<tr><td>7</td><td>Technology</td><td>1 Machine and infrastructure knowledge</td><td colspan="2" rowspan="2">0.811</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">0.67</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">N/A</td><td rowspan="2">No significant difference</td></tr>
<tr><td>8</td><td></td><td>2 Machine and infrastructure use</td></tr>
<tr><td>9</td><td>Economy</td><td>1 Costs for collecting, mining and processing</td><td colspan="2" rowspan="2">0.002</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">0.004</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">N/A</td><td rowspan="2">Significant difference between two sub-components</td></tr>
<tr><td>10</td><td></td><td>2 Cost volatility for collecting, mining and processing</td></tr>
<tr><td></td><td></td><td></td><td>1 to 2</td><td>1 to 3</td><td>1 to 4</td><td>2 to 3</td><td>2 to 4</td><td>3 to 4</td><td>1 to 2</td><td>1 to 3</td><td>1 to 4</td><td>2 to 3</td><td>2 to 4</td><td>3 to 4</td><td></td></tr>
<tr><td>11</td><td>Society</td><td>1 Social regulatory requirement</td><td rowspan="2">0.881</td><td rowspan="2">0.429</td><td rowspan="2">0.388</td><td rowspan="2">0.527</td><td rowspan="2">0.496</td><td rowspan="2">0.771</td><td rowspan="2">0.002</td><td rowspan="2">0.025</td><td rowspan="2">0.019</td><td rowspan="2">0.242</td><td rowspan="2">0.579</td><td rowspan="2">0.741</td><td rowspan="2">Delphi II only significant difference between all to 1 social regulatory</td></tr>
<tr><td>12</td><td></td><td>2 Working conditions</td></tr>
</table>

No	**Component**	**Sub-component / Indicator**	**Delphi survey I** (58 experts in total)			**Delphi survey II** (48 experts in total)			**Significant difference**
13		3 Human rights implications							requirement
14		4 Societal stability							
			1 (e.g. Environmental regulatory requirement) to 2 (e.g. **Total environmental impacts*)***	***1 to 3***	***2 to 3***	***1 to 2***	***1 to 3***	***2 to 3***	
15	Environment	1 Environmental regulatory requirement	0.526	N/A	N/A	0.302	N/A	N/A	No significant difference
16		2 Total environmental impacts							
Indicator selection									
17	Eligibility		***1 (e.g. Environmental regulatory requirement) to 2 (e.g.*** **Total environmental impacts*)***	***1 to 3***	***2 to 3***	***1 to 2***	***1 to 3***	***2 to 3***	
		1 Regulatory requirement - rule of law	0.355	N/A	N/A	0.007	N/A	N/A	Delphi II only significant difference between
		2 Regulatory requirement - operating license							
18	Technology	1 Use of machine and infrastructure – indexed annual rate of collection, mining recovery and processing re-	0.00	0.00	0.375	0.003	0.00	0.001	Significant difference between all to 1. Use of machine and infrastructure – indexed an-

No	Component	Sub-component / Indicator	**Delphi survey I** (58 experts in total)			**Delphi survey II** (48 experts in total)			**Significant difference**
		covery							nual rate of collection, mining recovery and processing recovery
		2 Use of machine and infrastructure – cumulative energy demand							
		3 Use of machine and infrastructure – exergy replacement costs							
19	Society	1 Working conditions – working hours	0.00	0.00	N/A	0.00	N/A	N/A	Significant difference between two sub-components
		2 Working conditions – non-fatal occupational injuries							
20	Society	1 Societal stability – political stability	0.001	N/A	N/A	0.001	N/A	N/A	Significant difference between two sub-components
		2 Societal stability – corruption perception							
21	Environment	1 Total environmental impacts– ecosystems	0.001	0.809	0.00	0.002	0.108	0.00	No significant difference between 'ecosystems' and 'human health'. Significant difference between 'ecosystems' and 'human health' with resource depletion.
		2 Total environmental impacts – resource depletion							
		3 Total environmental impacts – human health							

6.4.3 Framework consolidation for characterisation and evaluation

6.4.3.1 Scope

The scope of an accessibility investigation is to develop a broad and systematic framework for characterisation and evaluation at an early project development stage (Feiz and Ammenberg, 2017). **Early project development stage** means to be proactive in identifying research potential for a more in-depth investigation. These project development stages allow a comparison of mining deposits in the anthroposphere (MDA) and mining deposits in the geosphere (MDG), since they are based on the same (semi-) quantitative indicators. **Broad** means to cover several areas for relevance of sustainability. Additionally, composite indicators were used that can summarize complex and multi-dimensional reality (Saltelli *et al.*, 2005). **Systematic** refers to the utilization of a logical structure that enables comparability between different raw materials at country level and allows for integration to other frameworks, such as UNFC framework or criticality studies. The spatial scope is at country level. The temporal scope is annual, static, and requires periodic up-dates. The scope of data sources can include any scientific, and governmental reports, or personal communications.

The choice of scarce metals comprises a single raw material at a time, e.g. the materials with Neodymium-dioxide (Nd_2O_3). This supports the clarity and comparability of the accessibility evaluation. However, this can be a limitation to this framework if the operation of the first operational steps, i.e. operating a deposit, includes by-products. For example, Nd_2O_3 was first mined as a by-product from an iron mine in the Bayan Obo deposit (Goodenough, Wall and Merriman, 2017). To overcome this, when evaluating the indicators, it is important to add comments to each indicator.

The scope of the supply chain and waste management includes the operational steps, for MDA, namely (ai) collecting, (aii) manual and mechanical processing, (aiii) metallurgical extraction, and (aiv) refining. For MDG the following processes were investigated, namely (gi) mining, (gii) mineral processing, (giii) metallurgical extraction, (giv) refining. These investigated steps compare the processes of MDA and MDG, namely ai to gi, aii to gii, aiii to giii, to aiv to giv. The operational steps are described in section 6.5.2.2 and illustrated in Figure 23.

6.4.3.2 Uncertainty ranking

The case studies were investigated with limited underlying data, especially regarding MDA (Bach *et al.*, 2017). These data can have different scales or units and are often fragmented and non-harmonized (Mateus *et al.*, 2017). To overcome this, a data quality ranking (DQR) technique was applied. This addresses the issue of limited, fragmented and non-harmonized data. This DQR is commonly used in material flow analysis (Turner, Williams and Kemp, 2015), life cycle assessment (Weidema and Wesnæs, 1996) and geological availability assessment approach (Mateus *et al.*, 2017). The DQR was developed to include a Pedigree matrix with a ranking from 1 (high) to 5 (low) (details in Supporting information, section G.9). The following four criteria were identified:

i. Reliability (R) that states whether the data is based on measurement or non-qualified estimate.
ii. Completeness (Co), which evaluates whether the data was complete from a predefined area over an adequate period or if the data was unknown or incomplete.
iii. Temporal correlation (TeC) ranks whether the data is less than one year different to the year of study or more than ten.
iv. Geographical correlation (GC) assesses whether the data are from an area under study or from an unknown area. This can be stated as:

$$DQR = \frac{(\mathrm{R}+\mathrm{Co}+\mathrm{TeC}+\mathrm{GC}+Wi)*4}{i+4} \quad (1)$$

Where *R*, *Co*, *TeC* and *GC* are the matrix components, $W\,i$ is the weakest data quality criteria score obtained among i number of data quality indicators. To obtain a statement about the data quality, the calculated DQR score is ranked according the following criteria: DQR ≤ 1.6, ‘high quality’; DQR > 1.6 to ≤ 3, ‘fair quality’; and DQR > 3, ‘poor quality’ (see Supporting information, section **G.9**, for details).

6.4.4 Framework consolidation for characterisation: classes, sub-classes, components, sub-components, indicators

This refined and confirmed methodological framework builds on two sub-classes, namely availability and approachability, and six components (Chapter 5) (Figure 22). These components are underpinned by six sub-components and for each of these, two to three quantifiable indicators (Table 21). This methodological framework includes a minimal number of indicators, an equivalent weighting and no aggregation to provide a framework that is simple, transparent and adaptable to different approach users (Graedel *et al.*, 2012). It further includes a written statement on the general assumptions, such as possible limitations as described in LCA (ISO, 2006).

In contrast to Chapter 5, the aggregation of the sub-classification level approachability and availability was removed, since every aggregation includes a weighting, remains subjective and adds limited additional value to the interpretation of the results (Bach *et al.*, 2017).

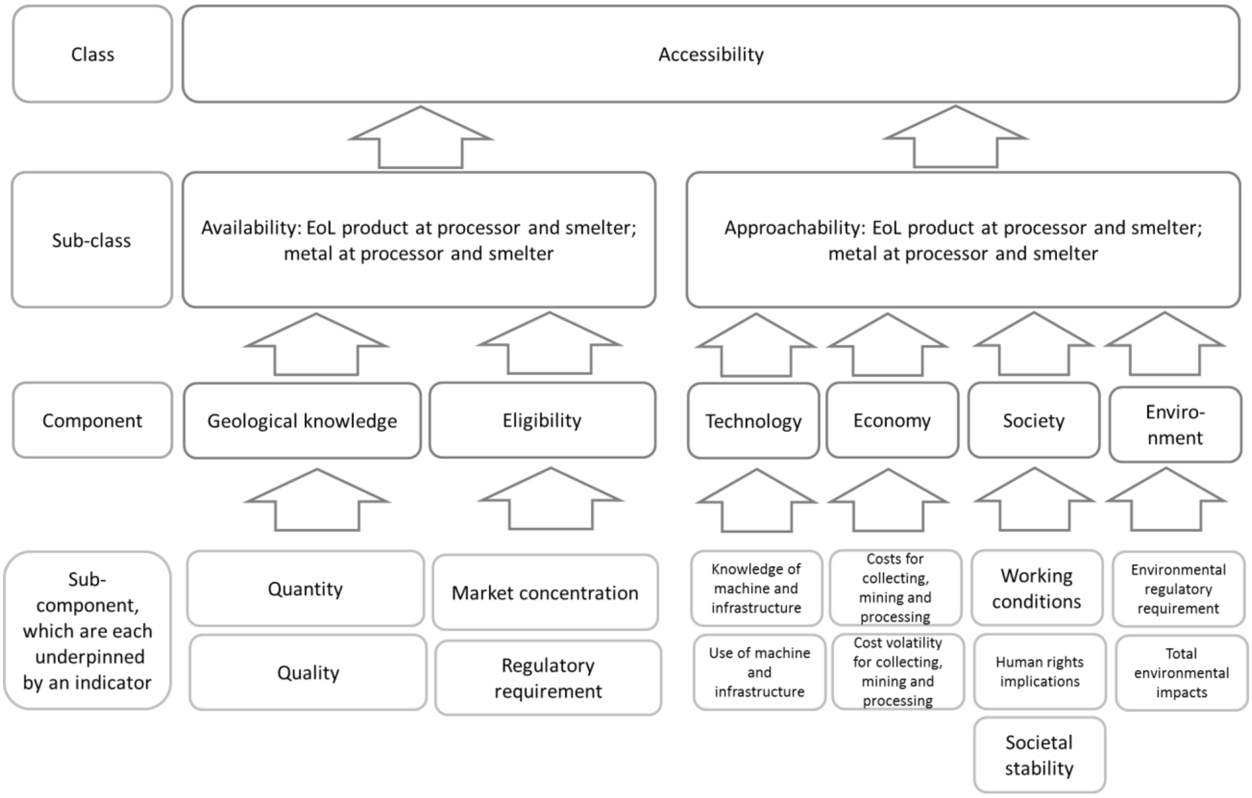


Figure 22: Refined, confirmed and consolidated evaluation framework for raw material accessibility with its sub-classes, its constituent components, sub-components. The sub-components are underpinned by indicators; see Table 20 for details. This framework is developed for an early project evaluation of national or corporate level but also common evaluation between mining deposits in the anthroposphere to geosphere.

An overview of the refined and confirmed sub-components and indicators is provided in Table 20. A detailed description is presented in Table 21. The calculation of each indicator is described in the Supporting information, section G.5. For some components, such as ‘geological knowledge’, the choice of indicators was rather straightforward, as similar (semi-) quantitative indicators were already used. Consequently, it can be said that these indicators are more bounded and easier to define. Other components, such as ‘technology’, ‘economy’, ‘society’, and ‘environment’ are more complex, which makes them more difficult to characterise with a few simple indicators and scorings. The strategy in dealing with the more complex components was to treat them as distinct but interpenetrating perspectives that overlap and mix with other components (adopted from Feiz and Ammenberg, 2017). To overcome this, a level of sub-components was included. For instance, for the component ‘technology’ the sub-classes (i) ‘**knowledge of machine and infrastructure development**’ and (ii) ‘**use of machine and infrastructure**’ were introduced. This was because through these two sub-components, a clear differentiation between the distinct technological phases, namely (i) development and (ii) use. For the components ‘society’ and ‘environment’, local and national impacts were included. This means that for ‘society’, on a local level the sub-components **working conditions**, **human rights implications** and on a national level the sub-component **societal stability** are considered. For 'environment', on a local level the sub-component **environmental regulatory requirement** and on a national level the sub-component **total environmental impacts** are considered.

A challenge was to formulate (composite) indicators that cover the most essential parts for each component and sub-components, without including too many aspects. This would have led to overcomplicated indicators, which would have resulted in a framework too difficult to implement. (Composite) indicators summarise complex, multi-dimensional reality, and enables comparability of complex dimensions. However, they can be simplistic or do not cover all aspects. Consequently, this could result in misleading conclusions (Saltelli *et al.*, 2005). To overcome this, it was important to not purely quantify the indicators, but also to state the wider context of information, such as assumptions, while characterising a case study. In this way, important information is included that otherwise is not fully covered by the indicators.

Table 20: Overview of the consolidated sub-components and (composite) indicators. The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability.

Class	Sub-class	Component	Sub-component	Used in consolidated framework	Indicator	Used in consolidated framework
Accessibility	Availability	Geological knowledge	Quantity	X	Annual mass flow	X
			Quality	X	Mass fraction	X
			Mine life		Time	
		Eligibility	Market concentration	X	Market concentration	
			Regulatory requirement	X	WGI 'rule of law'	
					Operating license	X
			Policy implementation		Policy perception	
	Approachability	Technology	Knowledge of machine and infrastructure	X	Knowledge of machine and infrastructure	X
			Use of machine and infrastructure	X	Indexed annual rate of collection, mining recovery and processing recovery	X
					Cumulative energy demand	
					Exergy replacement costs	
		Economy	Costs for collecting, mining and processing	X	Indexed costs in a country	X
			Cost volatility for collecting, mining and processing	X	Indexed cost volatility in a country	X
		Society	Social regulatory requirement		Social regulations and standards	
			Working conditions	X	Working hours	
					Non-fatal occupational injuries	X
			Human rights implications	X	Freedom of speech	X
			Societal stability	X	Political stability	X
					Corruption perception	
		Environment	Environmental regulatory requirement	X	Environmental regulations and standards	X
			Total environmental impacts	X	Ecosystems	X
					Resource depletion	
					Human health	X

6.4.5 Framework consolidation for evaluation: scoring

A score between one and three for each indicator using (semi-) quantitative ranges was defined. This score was derived iteratively while applying the framework, as seen in Table 22. This means that the scoring was developed and assigned while applying the case studies. For each resulting score I assigned a value to an indicator in the range of lower, moderate or higher accessibility was assigned (adopted from BGS, 2015; Oakdene Hollins, 2008). A more precise scoring and names denoted as 'low', 'moderate', and 'high' would not do justice to the low data certainty (section G.10 and G.11). Rather 'lower', 'moderate', and 'higher' were used. This is a refinement of the methodological framework development as applied in Chapter 5. The definitions of the ranges were reviewed and discussed iteratively.

A generic applicable score for the indicators is presented for: '**indexed annual rate of collection, mining recovery and processing recovery', freedom of speech, political stability, ecosystems and human health, operating license, environmental regulations and standards, market concentration**, and **indexed cost volatility in a country**. The scores for the indicators **mass**, **mass fraction** and **indexed costs in a country** were developed for this application: Nd_2O_3.

In scoring of 'lower', 'moderate', and 'higher', was implemented after literature reflection in Chapter 2, section 2.3.3.7. For all indicator results from the 48 'operational sections[29]', a linear ranking was applied if possible. This included for 'lower': 0 – 33.3%, 'moderate': >33.3 – 66.6%, and 'higher': 66.6 – 100% based on Oakdene Hollins (2008); and BGS (2015). This was used to score the indicator results from: **'indexed annual rate of collection, mining recovery and processing recovery', freedom of speech, political stability, ecosystems and human health**. For the indicator results that require an ordinal score of two, I implemented 'fulfilled' = 1 as 'higher' accessibility or 'not fulfilled' = 2 as 'lower' accessibility. This was the case for the indicator results such as: **operating license, environmental regulations and standards**. For the indicator results of **knowledge of machine and infrastructure** that require an ordinal score of four, I implemented 'lower' accessibility for knowledge that does not exist = 0, or is in research = 1, 'moderate' accessibility for scale up-phase = 2, and 'higher' accessibility for large scale production = 3. Existing scoring could be used for the indicator results of: **market concentration** (Weber and Heinrich, 2012), **indexed cost volatility in a country** (Spörri *et al.*, 2017).

The scores of the results from **mass** and **mass fraction** were case study specific. This means they need to be adopted for every raw material. The scores for the mass follow a logarithmic scale and correspond to terciles. Since annual mass flows in MDA are very small (Simoni *et al.*, 2015), the terciles in

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[29] Operational section means for each operational step, there is a distinct division part (adopted from Oxford Dictionaries, 2017g).

the logarithmic scale had to be adjusted: moderate accessibility level now aligns with the values of the case study from deposit in Australia, in which the mine was producing REO for the entire year.

The scores for **mass fraction** were developed based on dividing the sample in thirds corresponding to the result values. The scoring was tested for robust-ness by using the median to divide the sample in three parts, details in Table 22. The scoring of the indicator results from **indexed costs in a country** is case specific and was based on dividing the sample in thirds corresponding to the result values. The scoring was tested for robust-ness by using the median to divide the sample in three parts. The robustness testing showed the resulting accessibility score change was negligible. Details can be found in Table 22. In principle, these approaches could be implemented with other raw materials.

Table 21: Consolidation of components, sub-components and indicators. The combination of all components provides a statement on accessibility. The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability.

Component	Sub-component	Description	Indicator	Description	Unit	Reference source to identify data values
Geological knowledge	Quantity	The annual flow of a material originating from a deposit containing rock or End-of-Life products. This provides information about the annual mass flow of material collection/ mining and processing.	Annual mass flow	The flow of a material per year during collection/ mining and processing. Measured in metric tons.	[t]	USGS, industry; or company reports, books, and scientific papers such as Simoni *et al.,* (2015); Wall, (2014)
	Quality	A characteristic of a rock or End-of-Life (EoL) product. This provides an indication on the mass fraction of 1) Nd_2O_3 in an ore, REO-mineral concentrate, REO concentrate, or metal oxide; or 2) Nd_2O_3 in EoL product, EoL component, REO concentrate.	Mass fraction	The mass share of an 'ore' in any 'material'. Measured in metric ton per ton.	[t/t]	USGS, industry; or company reports, books, and scientific papers such as Simoni *et al.,* (2015); Wall, (2014)
Eligibility	Market concentration	The state or right of possessing something. This provides an orientation about the clarity of ownership during collection/ mining and processing.	Market concentration	Measure of annual market concentration of a defined small spatial area, e.g. producing country. Measured at each operational step by Herfindahl-Hirschman Index (HHI).	[no unit]	(Weber and Heinrich, 2012)
	Regulatory requirement	A rule or directive made and maintained by an authority. This provides an orientation on the quality of contract en-	Operating license	A permit from an authority to operate a process, such as collection/ mining and processing. Measured by existing certification about operating license, such as haz-	[no unit]	Industry or company reports such as (Kaufmann, Kraay and Mastruzzi, 2010).

Component	Sub-component	Description	Indicator	Description	Unit	Reference source to identify data values
		forcement and property rights.		ardous waste handling or atomic energy licensing board.		
Technology	Knowledge of machine and infrastructure	The information and skills about machines and infrastructure. This provides an indication about the existing knowledge on the development state of collection/ mining and processing.	Knowledge of machine and infrastructure	Information about existing knowledge. Measured at each operational step by scoring of whether knowledge does not exist, is in development or developed.	[no unit]	Scientific papers and technical reports.
	Use of machine and infrastructure	The application of machines and infrastructure. This provides an indication about the efficiency of machines and infrastructure.	Indexed annual rate of collection, mining recovery and processing recovery	The share of valuable material obtained from the operational steps: collection/ mining or processing (physical and metallurgical separation of either End-of-Life products or ores). Measured by these rates.	[%]	Scientific papers, technical reports, and indexes such as INSEAD (2015)
Economy	Costs for collecting, mining and processing	The monetary amount that has to be spent. This provides an orientation on the costs for collection/ mining and processing in a country.	Indexed costs in a country	Spent monetary amount of a country. Measured by material price, ratio of labour costs (with basis reference: year 2000) and price level (with OECD as basis reference: 100).	[indexed $/kg output material]	USGS, Trading Economics, OECD iLibrary, technical reports
	Cost volatility for collecting, mining and processing	Liability of costs to change rapidly and unpredictably. This provides an indication about the volatility of a market for collection/ mining and processing over the past 5 years.	Indexed cost volatility in a country	Spent monetary amount of a country. Measured along each operational step by difference of basis year of material price, labour costs (with basis reference: year 2000) and price level (with OECD as basis reference: 100) divided over same values but five years lower.	[%]	Spörri *et al.* (2017) USGS, Trading Economics, OECD iLibrary

Component	Sub-component	Description	Indicator	Description	Unit	Reference source to identify data values
Society	Working conditions	Working environment and all existing circumstances affecting labours in the workplace. This provides an orientation on the existing employment and non-fatal occupational injuries at a work place.	Non-fatal occupational injuries	The extent to which workers are protected from work-related hazards and risks at each operational step. Measured by international labour organisation, index (ILO) on non-fatal occupational injuries and proposed to measure the achievement of the Sustainable Development Goals (SDG). Note, this indicator requires further improvement, thus excluded. Excluded since the data sources do not allow comparability between countries. (ILO, 2017).	Number of non-fatal occupational injuries per 100'000 workers	(Bach *et al.*, 2017; ILO, 2017)
	Human rights implications	Implications of a right, which is believed to belong to every person. This provides an indication about the human rights situation of a country.	Freedom of speech	Voice and accountability includes at each operational step perceptions of the extent to which a country's freedom of expression and freedom of association. Measured by world governance indicator (WGI): Voice and Accountability (VA) (Kaufmann, Kraay and Mastruzzi, 2010).	[%]	(Tuma *et al.*, 2014; World Bank, 2016)
	Societal stability	Society that is not likely to undergo drastic changes. This provides an indication about the societal situation regarding stability of a country.	Political stability	The possibility of a government to be destabilized or overthrown by unconstitutional or violent means. Measured at each operational step by world governance (WGI) indicator, political stability and absence of violence/terrorism (PV) (Kaufmann, Kraay and Mastruzzi, 2010).	[%]	(Tuma *et al.*, 2014; BGS, 2015; World Bank, 2016)

Component	Sub-component	Description	Indicator	Description	Unit	Reference source to identify data values
Environment	Environmental regulatory requirement	A rule or directive providing a framework for environmental conditions made and maintained by an authority. This provides an orientation on the situation of environmental regulation and standard enforcement.	Environmental regulations and standards	An assessment from an authority to operate a process, such as collection/ mining and processing. Measured at each operational step by existing certification such as ISO 14001.	[no unit]	Industry or company reports such as (Immark AG, 2018).
	Total environmental impacts	A specific area in the world, which is affected by human activities. This provides an indication of the condition of ecosystems, resource depletion and human health related to collection/ mining and processing.	Ecosystems and Human health	- Ecosystem: impacts on the ecosystems using life cycle impact assessment. Measured at each operational step by the ReCiPe-method (indicator approach for life cycle impact assessment); - Human health: impacts on human health using life cycle impact assessment. Measured by ReCiPe-method (indicator method for life cycle impact assessment).	[impact points / kg metal oxide]	adopted from Graedel *et al.,* (2012); Spörri *et al.,* (2017); Wolfensberger *et al.,* (2015)

Table 22: Scoring of the accessibility level: lower -, moderate -, and higher along the operational steps for each indicator. The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability. N/A stands for not available.

Component	**Sub-component**	**Indicator**	**Generic or case specific scoring**	**Scoring along operational steps**				**Determination and justification of scoring**	**Reference**
				Mining / Collecting	**Mineral processing / Manual and mechanical processing**	**Metallurgical extraction**	**Refining**		
Geological knowledge	Quantity	Annual mass flow	Case specific	- lower: 0 – 0.4% operational step output / annual mass of world total REO - moderate: 0.4% - 4% operational step output / annual mass of world total REO - higher: >= 4 % operational step output / annual mass of world total REO Note: the moderate '0.4 - 4% boundary accounts for the in reality large annual production difference between mining companies.				- Determination of lower, moderate, higher: annual EoL or host rock / ‘annual mass of REO’	N/A as own development
	Quality	Mass fraction	Case specific	- lower: 0-1%, - moderate: >1% - 2% - higher: >=2%	- lower: 0-4%, - moderate: >4-8% - higher: >=8%	N/A, since the same result values of all case studies.	N/A, since the same resulting values of all case studies.	- Determination of lower, moderate, higher: quality / ‘average cut-off grade of REO’ The average cut-off grade was determined from: Mt. Weld: 4-7% (Lehmann, 2014) Mt. Pass: 5% (Lehmann, 2014) Zandkopsdrift: 1% (Wall, 2014) Average: 3.50%	N/A as own development
Eligibility	Market concentration	Market concentration	Generic	- lower: HHI >= 2,000 (≡ high market concentration) - moderately: HHI >1,000 – 2,000 (≡ moderate market concentration) - higher : HHI < 1,000 (≡ low market concentration)				- Justification: As applied in legal documents. The market share of the companies / country is squared so that the bigger companies have more weight	(Weber and Heinrich, 2012)
	Regulatory requirement	Operating license	Generic	- lower: non-existing operating license: 0 ; - higher: existing operating license 1				N/A	N/A as own development
Technology	Knowledge of	Knowledge of ma-	Generic	-lower: knowledge does not exists = 0, or is in research = 1 - moderate: scale up-phase = 2				N/A	N/A as own develop-

Component	**Sub-component**	**Indicator**	**Generic or case specific scoring**	**Scoring along operational steps**				**Determination and justification of scoring**	**Reference**
				Mining / Collecting	**Mineral processing / Manual and mechanical processing**	**Metallurgical extraction**	**Refining**		
	machine and infrastructure	chine and infrastructure		- higher: large scale production = 3					ment
	Use of machine and infrastructure	Indexed annual rate of collection, mining recovery and processing recovery	Generic	- lower: 0 – 33.3%, - moderate: >33.3 – 66.6% - higher: 66.6 – 100%				- Justification: the indexed rate for both MDA and MDG can range from 1-100% as confirmed in various references from both MDA and MDG (Reck and Graedel, 2012; Ayres and Peiró, 2013; Peiró and Méndez, 2013; EC, 2017b), consequently I split the range equally into thirds.	N/A as own development
Economy	Costs for collecting, mining and processing	Indexed costs in a country	Case specific	- lower: >= 2% (≡ high risk) - moderate: >1 – 2 % (≡ moderate risk) - higher: 0 – 1% (≡ low risk) operational step output / annual average annual Nd_2O_3 price	- lower: >= 4% (≡ high risk) - moderate: >2 – 4% (≡ moderate risk) - higher: 0 – 2% (≡ low risk) operational step output / annual average annual Nd_2O_3 price	- lower: >= 13% (≡ high risk) - moderate: >7 – 13 % (≡ moderate risk) - higher: 0 – 7% (≡ low risk) operational step output / annual average annual Nd_2O_3 price	- lower: >= 94% (≡ high risk) - moderate: >62 – 94 % (≡ moderate risk) - higher: 0 – 62% (≡ low risk) operational step output / annual average annual Nd_2O_3 price	- Determination of lower, moderate, higher: annual indexed costs / 'average Nd_2O_3 price of 2015 from USGS, (2016)' Note, since the divisor is an average price, which can also be lower than the 'output of the operational step output, the result can be higher than 100%. Scoring was developed by dividing the sample in thirds corresponding to the result values. The scoring was tested for robustness by using the median to divide the sample in three parts. The robustness testing showed the resulting accessibility	N/A as own development

Component	Sub-component	Indicator	Generic or case specific scoring	Scoring along operational steps				Determination and justification of scoring	Reference
				Mining / Collecting	Mineral processing / Manual and mechanical processing	Metallurgical extraction	Refining		
								score change was negligible.	
	Cost volatility for collecting, mining and processing	Indexed cost volatility in a country	Generic	- lower: >= 200% (≡ high risk) - moderate: 100 – 200% (≡ moderate risk) - higher: 0 – 100% (≡ low risk)				- Justification: used the lower range from original 0 – 500%, since all data values were between 0 to 200%.	(adopted from Spörri *et al.,* 2017)
Society	Working conditions	Non-fatal occupational injuries	Generic	N/A				N/A	N/A
	Human rights implications	Freedom of speech	Generic	- lower: 0 – 33.3%, - moderate: >33.3 – 66.6% - higher: 66.6 – 100%				N/A	N/A as own development
	Societal stability	Political stability	Generic	- lower: 0 – 33.3%, - moderate: >33.3 – 66.6% - higher: 66.6 – 100%				N/A	(BGS, 2015)
Environment	Environmental regulatory re-requirement	Environmental regulations and standards	Generic	- lower: non-existing environmental regulations and standard = 0, - higher: existing environmental regulations and standards = 1				N/A	N/A as own development
	Total environmental impacts	Ecosystems and Human health	Generic	Ecosystems and human health combined: - lower: > 66.6 - >100Pt (≡ high impact) - medium: >33.3 – 66.6Pt (≡ moderate impact) - higher: 0 – 33.3Pt (≡ low impact)				Justification: adopted from original range 1 (0Pt) to 5 (100Pt) Graedel *et al.* (2012); Spörri *et al.* (2017)	adopted from Graedel *et al.* (2012); Spörri *et al.* (2017)

6.5 Framework application

In this section the framework is applied to show the utility of the accessibility evaluation. This section consists of the sub-sections 'method' and 'result and discussion'.

6.5.1 Framework application: method

In these sub-sections, four cases are described, followed from the 'operational steps'[30]. Then all MDA and MDG case studies were characterised, as described in Table 21, and evaluated, as described in Table 22, along the operational steps (Figure 23). A detailed description of this method can be found in section 3.4.

6.5.2 Framework application: case study description

In these sub-sections, four cases are described, followed from the 'operational steps'. Then all MDA and MDG case studies were characterised, as described in Table 21, and evaluated, as described in Table 22, along the operational steps (Figure 23).

6.5.2.1 Four case studies

The selected case studies are based on the initial application in Chapter 5 and have a solid data basis. From this initial application, the case studies of 'high accessibility', i.e. Earth's crust deposit with Nd_2O_3 related to Australia / Malaysia, had a solid data basis and is investigated further. This MDG is complemented with two other case studies that had a solid data basis: Earth's crust deposit related to China and Earth's crust deposit related to the USA. The MDG was complemented with a case study from MDA that could resort to a solid data basis, namely HDDs with deposits in Switzerland, and processing in Germany, Austria, Japan, and Vietnam (Hügi and Baudin, 2015). The year of investigation is 2015. The raw material, metal oxide at smelter, is Nd_2O_3, as seen in Figure 23.

1. MDA, EoL HDDs with deposit in Switzerland, and processing in Germany, Austria, Japan, and Vietnam: The HDDs deposit in Switzerland contains Neodymium–Iron–Boron ($Nd_2Fe_{14}B$) permanent magnets. In the HDDs' permanent magnets, the Nd is found in pure and large quantities (Lixandru *et al.*, 2017). The HDDs are used widely and are expected to be used with similar quantities until 2030 (Ueberschaar and Rotter, 2015) but likely to be replaced by solid state disks (SSD), which do not contain $Nd_2Fe_{14}B$ permanent magnets (Thiébaud *et al.*, 2016). For comparability all Nd-results with the Earth's crust deposits were converted to Nd_2O_3. This case study was selected for the following reasons: (i) relevant data are available (BAFU, 2015b), (ii) the Nd from HDDs is currently not recycled (Habib, Parajuly and Wenzel, 2015), (iii) that it exists in large quantities and is widely used, and (iv)

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[30] The action to control the functioning of a specific process along the supply chain and waste management (adopted from Oxford Dictionaries, 2017e).

Switzerland, Japan, Germany and Austria are a case study for developed countries, whereas Vietnam is a case study for developing countries.

2. MDG, Earth's crust deposit in Australia / Malaysia: The Mt. Weld geological deposit in Australia is owned and operated for mining and mineralogical processing by Lynas Corporation Ltd. The concentrated mineral is metallurgically extracted and refined Malaysia (Wall, 2014). This case study was selected as (i) relevant data are available (Schmidt, 2013; Ali, 2014; Jaireth, Hoatson and Miezitis, 2014), (ii) the site has an assured production by means of a 10 year raw material purchase contract with Japan (Lynas, 2010), and (iii) Australia is an example for developed countries, whereas Malaysia is for developing countries.

3. MDG, Earth's crust deposit in China: The Bayan Obo mine in China is currently operated by the state-owned enterprise, Baotou Rare Earth Group (Klinger, 2015). This case study was selected because (i) it is the mine with the largest world-wide market share (Wall, 2014), and (ii) is being largely studied (Yang *et al.*, 2011; Haque *et al.*, 2014; Klinger, 2015), and (iii) China is a case study for developing countries.

4. MDG, Earth's crust deposit in the USA: The Mt Pass mine in the USA was operating until terminating its production in the first quarter of 2015. In mid-2015, Molycorp Inc. filed bankruptcy (Topf, 2017). This deposit has been chosen as a case study since (i) it was formerly the largest REE mine in the world (Machacek and Fold, 2014) and thus being largely studied (Humphries, 2010), (ii) it implements high social and environmental standards (Currie, 2012) and (iii) the USA is a case study for a developed country.

6.5.2.2 Operational steps

An overview of possible operational steps of both MDA and MDG is shown in Figure 23. For MDA, the following operational steps were considered: collection, manual and mechanical processing, metallurgical extraction, and refining as identified in Wolfensberger *et al.* (2015). A summary of how these operation steps were considered in this study is outlined below (based on Wolfensberger *et al.* (2015).

Collection: EoL personal computers and laptops were collected in Switzerland (SWICO System) (Wolfensberger *et al.*, 2015).

Manual and mechanical processing:

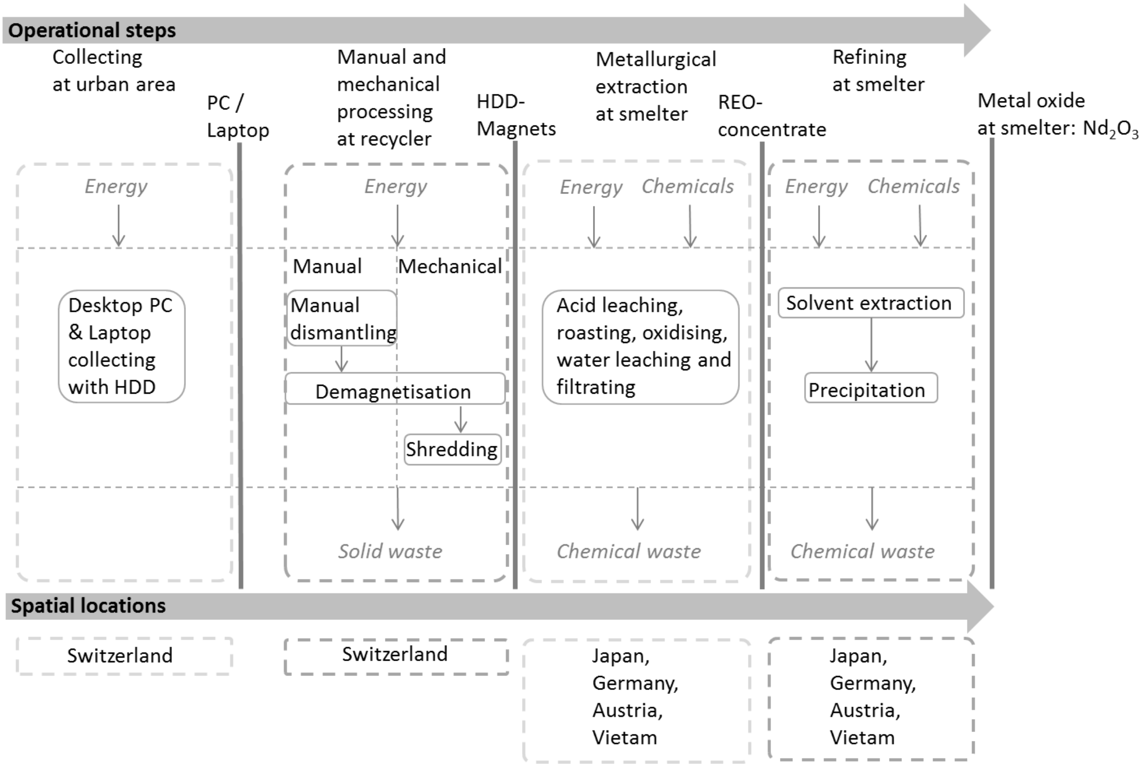
Manual processing: this would include manual dismantling from PCs, respectively Laptops, to HDDs, followed by heated demagnetization to obtain the magnets without magnetic properties (Wolfensberger *et al.*, 2015). The recovery rate was assumed at about 90% (Sprecher *et al.*, 2014).

Mechanical processing: HDDs are heated, demagnetised, shredded (Wolfensberger *et al.*, 2015) and finally manually dismantled (Sprecher, Kleijn and Kramer, 2014). The recovery rate was assumed at about 10% (Sprecher *et al.*, 2014).

Metallurgical extraction: Magnets are acid leached, roasted / oxidised (Yang *et al.*, 2017), then water is leached and finally filtered (Simoni *et al.*, 2015). The recovery rate was assumed at about 90% (Gupta and Krishnamurthy, 2005).

Refining: The REO concentrate is extracted by solvents and then precipitated (Yang *et al.*, 2017).The final product is the individual REO: *inter alia* Nd_2O_3. The recovery rate was assumed at about 90% (Peiró and Méndez, 2013).

a) Mining deposits in the anthroposphere (MDA)



b) Mining deposits in the geosphere (MDG)

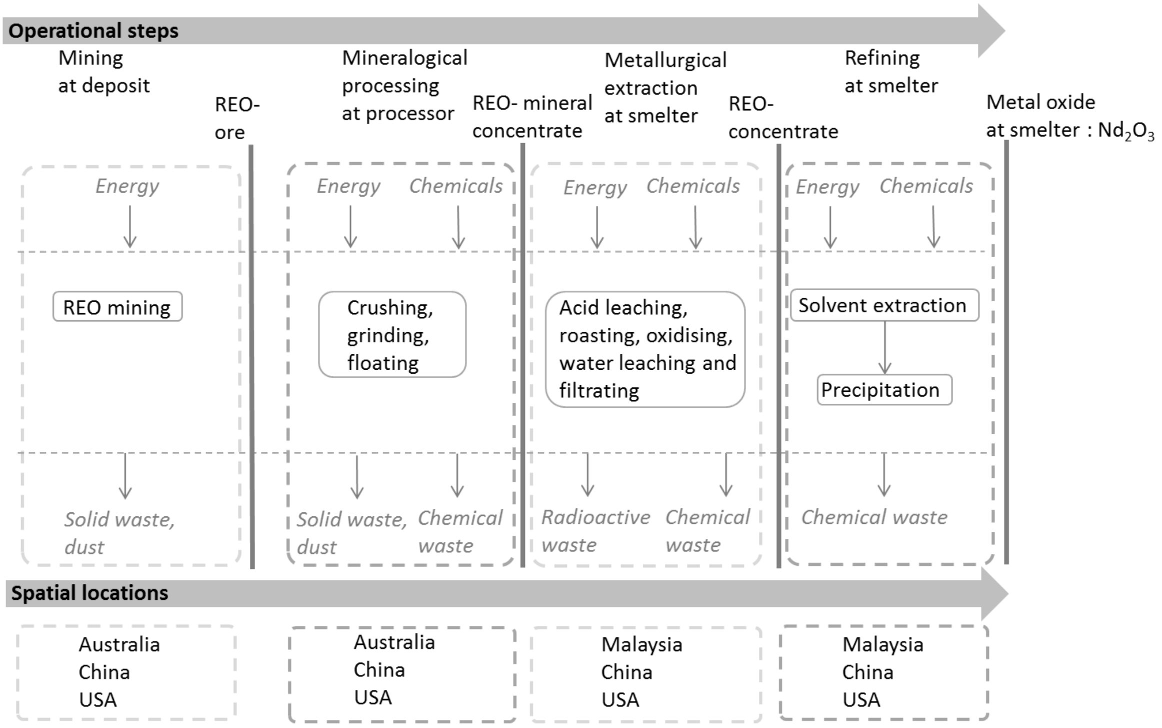


Figure 23: Operational steps and spatial locations for mining rare earth oxide (REO), a) mining deposits in the anthroposphere from the End-of-Life (EoL) product Desktop PC, Laptop with HDDs, b) mining deposits in the geosphere with selected REO deposits (adopted from Althaus, *et al.,* 2007; Hügi and Baudin, 2015; Long *et al.,* 1998; Simoni, 2012; Wall, 2014).

For MDG, the following operational steps were considered: mining, mineral processing, metallurgical extraction and refining (Figure 23). The operation of metallurgical extraction and refining in MDG is similar to MDA.

Mining: The ore deposits are mined to extract crude REO ore. Waste products of mining activities (overburden, top soil and waste rock) are typically backfilled into the mine (Sprecher *et al.*, 2014); hence, the losses were neglected, i.e. recovery rate of 100%.

Mineral processing: The crude ore rocks are crushed, ground and separated to produce a mineral concentrate and tailing waste. Recovery rates were assumed as 50% at Bayan Obo, China, 90% at Mt. Pass, USA and 75% at Mt. Weld, Australia (Peiró and Méndez, 2013).

Metallurgical extraction: The concentrates are separated by flotation (Gupta and Krishnamurthy, 2005). These are then acid leached, oxidised/roasted, water leached and finally, filtered (Simoni *et al.*, 2015). The highly radioactive elements, Thorium and Uranium, are produced as by-products and require special treatment (Schmidt, 2013). The recovery rate of this process is about 72% at Bayan Obo, China; about 92% in Mt. Pass, USA; and about 90% in Malaysia (adopted from Peiró and Méndez, 2013).

Refining: There REO concentrates are washed by solvents, precipitated (Althaus, *et al.*, 2007; Simoni *et al.*, 2015) and then filtered (Sprecher *et al.*, 2014). The recovery of this process is about 90% (adopted from Peiró and Méndez, 2013).

6.5.3 Framework application: results and discussion

First the results of the characterisation and then the evaluation of raw material accessibility are discussed.

6.5.3.1 Characterisation of raw material accessibility

The results and discussion of the characterisation of raw material accessibility are provided in subsections 5.6.2.1.1 to 5.6.2.1.6, which are named according to the six components. Each component describes the results of the subsequent sub-components and indicators in the bracket of both MDA and MDG. Detailed information regarding the data sources, determination, assumptions and uncertainty ranking can be found in Supporting Information, as an overview in G.6, in details for MDG G.7 and for MDA in G.8. The uncertainty ranking can be found for MDG in G.10 and for MDA in G.11. Generally, the data values are from the year 2015 but can range from 2011 to 2017. The data quality is as expected to be rather low for investigating an early project development stage. For the following characterisation, a graphic illustration was made, however in some instances the content is insufficient for this to be possible.

5.6.2.1.1. Geological knowledge

Overall, the results related to ‘geological knowledge’ are important knowledge for assessing future ‘access / use’ of a mineral resource (Mateus *et al.,* 2017). Since this is an investigation at an early project development state, the influence of mining the Nd_2O_3 as a by-product from MDG and MDA, such as HDD that are an EoL product from a Desktop PC and Laptop.

The results of the sub-component **quantity** (indicator: **annual mass flow**) show a 100 to 200 times lower factor of mining the deposits in the anthroposphere to the geosphere (Figure 24). 55,383 t were extracted from Chinese deposits, 1,992 t in Australia, and 238 t in the USA (note that the value for the USA refers only to mining in the first quarter).

Concerning the sub-component **quality** (indicator: **mass fraction**), the **mass fraction** in products increased during each operational step (i.e. from mining/collection to refining). Concerning MDA and MDG, the **mass fraction** of Nd_2O_3 in collected products was 100 times higher than in the geologically mined ore. Concerning MDG, the lowest **mass fractions** were found in China. Regarding MDA, the long-term availability of Nd_2O_3 from HDD is limited. This is due to the emergence of solid state discs (Thiébaud *et al.*, 2016).

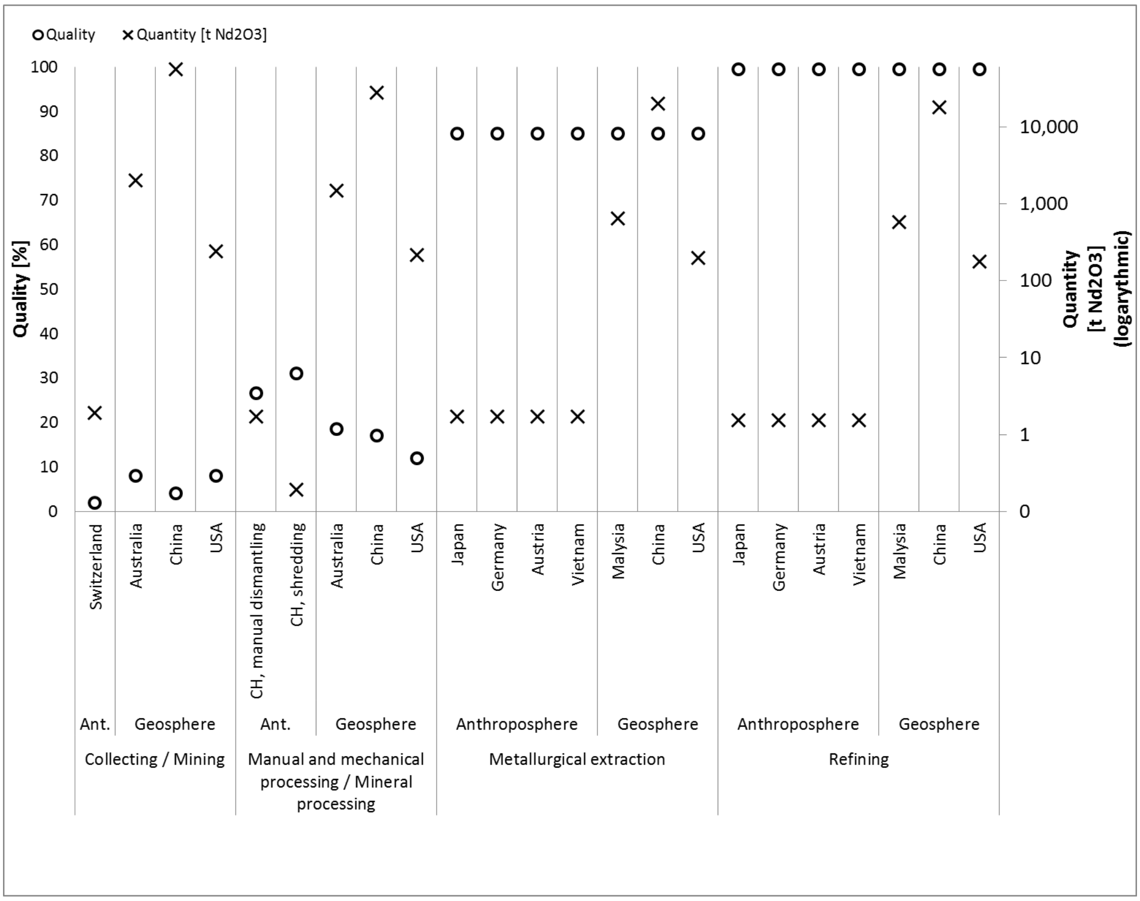


Figure 24: The results of quantifying the component 'geological knowledge' with the sub-components quality (circles) and quantity (crosses and logarithmic scale) for mining deposits in the anthroposphere (MDA) and mining deposits in the geosphere (MDG).

5.6.2.1.2. Eligibility

Overall, the sub-component results **market concentration** (indicator: **market concentration**) and **operating license** (indicator: **operating license**) of each country showed little change along the operational steps. In MDA, the results of **market concentration** demonstrated low values. The collection resulted as 0.01 (no unit) with > 1,000 collection points. The manual and mechanical processing demonstrated as 83 (no unit), which comprise 11 authorised processing companies. The metallurgical extraction and refining was not quantifiable, as this process does not exist. For MDG, the **market concentration** resulted in China: 7,170 (no unit) Australia / Malaysia: 65 (no unit) and USA: 11 (no unit) during all operational steps. The high **market concentration** in China was confirmed with 95% of the world REO production between 2010 to 2014 (EC, 2017b). However, the case study from China neglects 40% illegal exporting from China (Machacek *et al.*, 2015).

In both MDA and MDG, the results of **operating licence** (indicator: **operating license**) indicated that 'existing **operating licenses**' were held for all locations. All results were obtained on the basis of assuming that all investigated operators run their business on a daily basis and thus hold an **operating**

license. The results of operating licence are important basic information for an early project development statement, since a detailed investigation is conducted before issuing the permit. However, the statement from this sub-component alone provides limited knowledge on a broad understanding about the accessibility situation.

5.6.2.1.3. Technology

The results of the sub-component **knowledge of machines and infrastructure** (indicator: **knowledge of machines and infrastructure**) demonstrated as 'large scale production' for the following operational steps: collection in MDA, metallurgical extraction in MDA and MDG, and refining in MDA and MDG. For the operational step manual and mechanical processing in MDA, the result was 'in research'. The outcome of **knowledge of machine and infrastructure** is important fundamental information for an early project development statement, since it provides a general statement on the development status of a technology. However, the statement from this sub-component alone provides limited knowledge for a broad understanding of the accessibility situation.

The results of the sub-component **use of machine and infrastructure** (indicator: **indexed annual rate of collection, mining recovery and processing recovery**) demonstrated for MDA: an indexed rate of 51% for collection in Switzerland, an indexed rate of 91.8% for manual processing in Switzerland, an indexed rate of 10.2% for mechanical processing in Switzerland, an indexed rate of >85 % for metallurgical extraction in Japan, Germany, Austria and Vietnam, and an indexed an indexed rate of >90% for refining in Japan, Germany, Austria and Vietnam. The results of the MDG case studies showed an indexed rate of 100% for mining in Australia, China and the USA; an indexed rate of 51% for mineral processing and metallurgical extraction in China, >70 % for mineral processing and metallurgical extraction in Australia and the USA; and an indexed rate of >90% for refining in Australia, China and the USA. These results base on composite indicators that assume there is continuous innovation in a country. Consequently, the results can be compared relatively to each other and provide an indication on the general situation.

The technology of MDA's manual and mechanical processing is currently a challenge, since the $Nd_2Fe_{14}B$ magnets have high magnetic strength. This strength is the reason why the magnets stick to any ferrous surface, which includes the surfaces of operating plants (Habib, Hamelin and Wenzel, 2016). Generally, the importance of the sub-component **use of machine and infrastructure** can be underpinned by the very similar indicator recycling rate, which is an often-used measure to determine the resource efficiency of a society (Haupt, Vadenbo and Hellweg, 2017).

5.6.2.1.4. Economy

The results of the sub-component **costs for collecting, mining and processing** (indicator: **indexed costs in a country**) in MDA demonstrated as 0.5 indexed $ / kg HDD for collection in Switzerland, 61.9 indexed $ / kg magnets for manual processing in Switzerland, 0.1 indexed $ / kg magnets for mechanical processing in Switzerland, no results for metallurgical extraction, 40 – 46 indexed $ /kg Nd_2O_3 for the refining in Japan, Germany, Austria, and 12 indexed $ /kg Nd_2O_3 for refining in Vietnam. The results of MDG showed a steep increase along the operational steps. The results of the last operational step, refining, demonstrated 46 indexed $ /kg Nd_2O_3 in Malaysia and the USA and 24 $ /kg Nd_2O_3 in China. Surprisingly, the cost results of refining in Japan, Germany, and Austria were comparable to the results of refining in Malaysia and the USA. However, it should be noted the costs can vary largely depending on each exploitation project (Machacek *et al.*, 2015). Additionally, these results base on a composite indicator that includes the raw material price, human labour and production costs. Consequently, the results can be compared relative to each other and provide an indication on the general situation.

The results of the sub-component **cost volatility for collecting, mining and processing** (indicator: **indexed cost volatility in a country**) is useful additional information for understanding the volatility of a market. However, the raw data was very limited for all operational steps and varies between years. As a consequence, these results provide limited additional information. Nevertheless, in the RESCHECK evaluation, this sub-component was applied and resulted in important knowledge for comparing different metals. For instance, the metal Nd resulted in a high price volatility (Spörri *et al.*, 2017).

5.6.2.1.5. Society

The results of **human rights implications** (indicator: **freedom of speech**) and **societal stability** (indicator: **political stability**) demonstrated no difference between MDA and MDG, as seen in Figure 25. Specifically, the results of both sub-components, respectively indicators, demonstrated a rate of > 65% for all operational steps in Switzerland, Japan, Germany, Australia and the USA, a rate of 30 - 60% for metallurgical extraction and refining in Malaysia, and a rate of < 30% for all operational steps in China and Vietnam. These results indicate a clear difference between developing and developed countries. Generally, these results provide important information for the UNFC classification, in particular for identifying relevant social contingencies (UNFC, 2017a, b, d). However, these results are based on a composite indicator that includes various sources of information, such as Freedom House, Transparency International Global Corruption Barometer, World Economic Forum, and World Bank.

Consequently, the results can be compared relative to each other and provide an indication on the general situation.

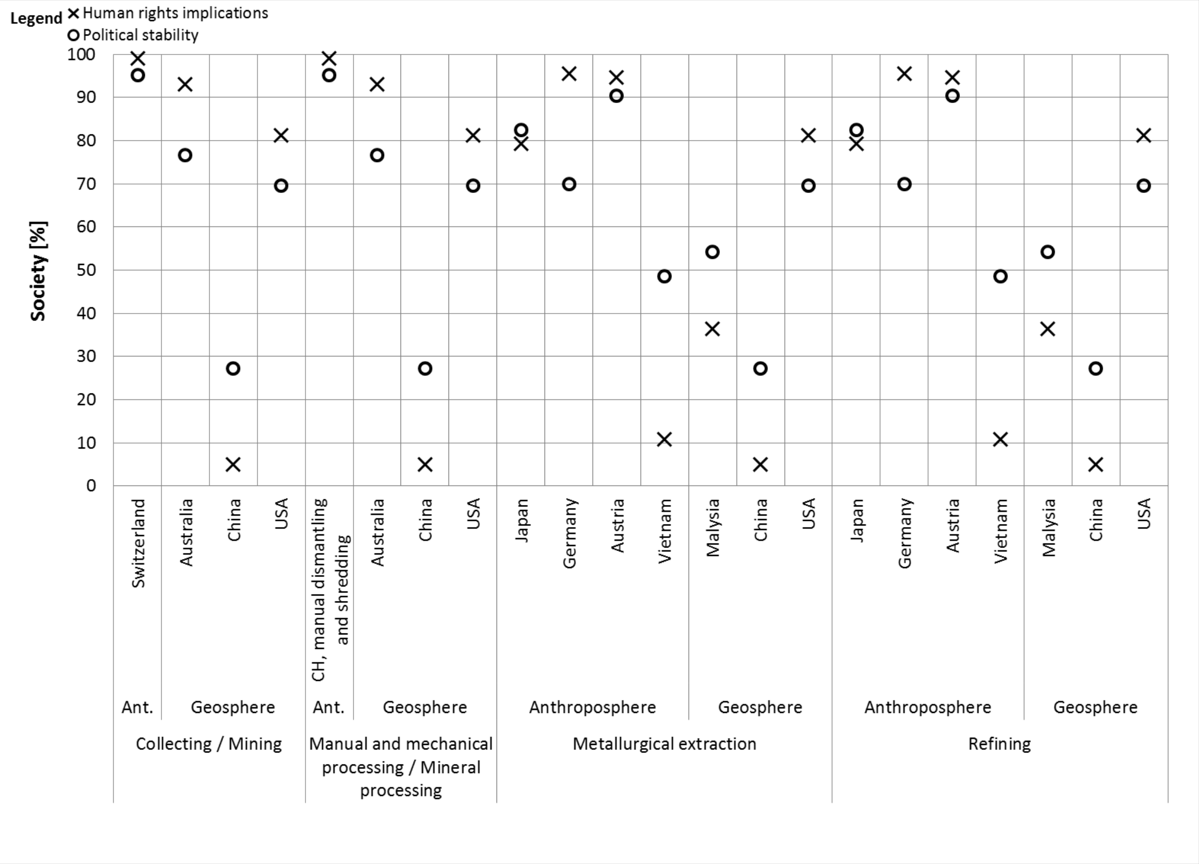


Figure 25: The results of quantifying the component 'society' with the sub-components freedom of speech (crosses) and societal stability (circles) for both mining deposits from the anthroposphere (MDA) and mining deposits from the geosphere (MDG). 0% is low and 100% is high.

5.6.2.1.6. Environment

The sub-components **environmental regulatory requirements** (indicator: **environmental regulations and standards**) and **total environmental impacts** (indicators: **ecosystems and human health**) resulted in no difference between MDA to MDG. Since the data availability was low, only very few results could be obtained. The MDA resulted as 0.0011 impact Pt from collection in Switzerland, 0.599 impact Pt from manual processing in Switzerland, 0.815 impact Pt for mechanical processing in Switzerland. The MDG resulted as 0.338 impact Pt for mining in China, 4.490 impact Pt for metallurgical extraction and refining in China (Wolfensberger *et al.* 2015). These last high values resulted from applying potent chemicals, such as sulfuric and hydrochloric acid (Schmidt, 2013). Moreover, the metallurgical extracting concentrates the radioactive Uranium and Thorium in MDG (Klinger, 2015). The results of the total environmental impact were confirmed by investigations from Simoni *et al.* (2015). Generally, these results are valuable basic information for the UNFC classification, particularly for identifying relevant environmental contingencies (UNFC, 2017a, b, d). However, these results are based on a composite indicator that assumes an early project stage development for developed countries that have enforced environmental regulation. Consequently, the results can be compared relative to each other and provide an indication on the general situation.

6.5.3.2 Evaluation of raw material accessibility

The results and discussion of the evaluation of raw material accessibility is provided in this sub-section. For readability, in this sub-section, the components are highlighted with quotation marks. The results of the evaluation are shown in Table 23 for MDA and in Table 24 for MDG in the form of an evaluation grid along the supply chain and waste management, which can be used to identify hotspots for improvements. This grid shows the results of each indicator with subsequent sub-components, components and sub-classes. The score was 'lower', 'moderate' or 'higher' accessibility. Numerical results were not shown, since this is an early project development evaluation that aims to identify potentials for further in-depth investigations. The scored results provide a general overview of strengths, weaknesses, opportunities, and uncertainty of the current situation. These results can be used to review the supply of a raw material, here Nd_2O_3. Consequently, the current situation on the accessibility of a raw material can be better understood. In numbers, I was able to quantify the accessibility of 2 sub-classes, 6 components (that includes the subsequent sub-components and indicators), and 4 operational steps for both of MDA and MDG with four case studies. This leads to a total of 39 operational sections out of 48, as there was a lack of data.

Considering the results of each operational step (column) separately, first the results of MDA and then of MDG were describe. The results of MDA indicate, generally, the accessibility level can vary along the operational steps. In detail, the collection step is hampered at 'lower' to 'moderate' accessibility in 'geological knowledge', partly 'technology' and partly 'economy'. For instance, the results of 'technology' at the mechanical processing step scored 'lower' accessibility. This could be overcome by scaling up the extent of manual processing, which scored as 'higher' accessibility. An example for manual processing opportunities, this processing potential was researched at a Swedish recycling plant. It was found that every month about 2,500kg HDDs could be separated. These HDDs could be processed to 27.5–102.5 kg of $Nd_2Fe_{14}B$ magnets per month (Lixandru *et al.*, 2017). The results of metallurgical extraction and refining are generally 'high' with exceptions in 'geological knowledge**', quantity** and partly 'economy'. The results of MDG show generally that accessibility is hampered, with 'lower' to 'moderate' in 'geological knowledge' (partly), 'eligibility', 'society', 'environment' but not 'technology' and 'economy'. This indicates there may be a discrepancy in the accessibility between MDA and MDG. Note, at both MDA and MDA for 'geological knowledge', **quality**, since there was a single result value, no scoring of 'lower', 'moderate', and 'higher' could be assigned.

Considering the components (rows), the results of 'geological knowledge' scored as 'lower' to 'moderate' accessibility for all case studies apart from China. The results for the components economy', 'society' and 'environment' showed a bipolar accessibility situation between developing and developed countries. The results for the component 'economy' demonstrated a score of 'higher' accessibility for the developing countries, whereas for the developed countries, a score of 'lower' accessibility during metallurgical processing and refining was found. In contrast are the results of 'society' and 'environment', namely the developing countries scored 'lower' accessibility and the developed countries scored as 'higher' accessibility. This indicates there is likely an imbalanced situation between developing and developed countries. For instance, developing countries China and Vietnam can produce metals much more cheaply, use slightly less efficient technologies, and have a distinctively higher impact on society and the environment than developed countries, such as Switzerland, Australia and the USA. Similarly, Bach *et al.* (2017) emphasised that in developing countries the compliance with social and environmental standards was low. Also Ali (2014) pointed out there were more stringent safety enforcements in developed countries such as Solvay in France (Ali, 2014). These findings are confirmed by the expert comments from the Delphi study, as seen in section 6.4.2. An overview of the assumptions is provided in section 6.5.3.1.

Considering the results on a more aggregated level, as shown in Table 23 and Table 24, the results of the sub-classes 'availability' and 'approachability' can be investigated. This perspective not only provides an overview of the two sub-classes but also an indirect statement on the class 'accessibility'. It can be used to review each spatial location to learn more about sustainability from different viewpoints, and for comparison of different sub-classes, components, and operational steps. For example, looking at the 'availability' results for MDA, scores of 'lower' accessibility was demonstrated for the component 'geological knowledge' and the sub-component 'quantity' for all operational steps and the sub-component 'quality' for collection. Still for MDA, scores of 'higher' accessibility was demonstrated for MDA at the component 'geological knowledge' and the sub-component 'quality' for the operational steps manual and mechanical processing, metallurgical extraction, and refining. 'Higher' accessibility was also demonstrated for the component 'eligibility' and its sub-components 'market concentration' and 'regulatory requirements'. This shows that the sub-components of the sub-class 'availability' are generally scored as 'higher', with the exception of the sub-component 'quantity' ('lower').

For example, looking at the 'availability' results for MDG, scores with 'various' accessibility levels were demonstrated at the component 'geological knowledge' and mainly 'higher' accessibility was demonstrated for 'eligibility' with 'lower' accessibility for the indicator 'market concentration' in China. To make a statement on the trend from the results of ‘geological knowledge’, these results indicate more information is required to confirm these results. Similar observations about requiring more information on ‘geological knowledge’ of MDG was stated by Goodenough, Wall and Merriman (2017).

Considering the ‘approachability’ results for MDA, scores with ‘various’ accessibility levels were demonstrated at the components ‘technology’ and ‘economy’ for all operational steps. Mainly scores with ‘higher’ accessibility resulted from the components ‘environment’ and ‘society’. To ensure accessibility, these results indicate there are particular challenges regarding ‘technology’ and ‘economy’. Similarly Habib, Parajuly and Wenzel (2015) confirmed the challenges regarding ‘technology’ with HDDs.

Considering the ‘approachability’ results for MDG, most accessibility level scored ‘higher’ accessibility at the components ‘technology’ and ‘moderate’ to ‘higher’ accessibility for ‘economy’ for all operational steps. Scores with ‘various’ accessibility levels were demonstrated at the components ‘society’ and ‘environment’. These results represent a reverse situation to the approachability results for MDA. This indicates that lessons might be learnt from both MDA and MDG. In particular, the scores with ‘various’ accessibility levels on ‘society’ and ‘environment’ indicate potential for further clarification.

Considering the data quality ranking of the results in Table 23 and Table 24, which affected the validity of the evaluation (Schwab, Zoboli and Rechberger, 2016). The component ‘geological knowledge’ resulted in a data quality of ‘high’ (2%), ‘fair’ (61%), and ‘poor’ (36%). The component ‘eligibility’ demonstrated ‘high’ (6%) and ‘fair’ (94%) data quality. The component ‘technology’ resulted in ‘fair’ (70%) and ‘poor’ (30%) data quality. The component ‘economy’ demonstrated a data quality of ‘fair’ (66%) and ‘poor’ (34%). The component ‘society’ resulted in ‘fair’ (100%) data quality. The component ‘environment’ demonstrated a data quality of ‘high’ (31%), ‘fair’ (34%), and ‘poor’ (34%). Overall, most of the data were ‘fair’ quality. This emphasises on the dearth of ‘high’ quality data for the accessibility evaluation and denotes a substantial source of uncertainty (Turner, 2016).

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Table 23: The results of the accessibility evaluation related to mining deposits in the anthroposphere (MDA). The scoring bases on HDD sourced from laptops and desktop PC in Switzerland in 2015 along the operational steps: collecting, manual and mechanical processing, metallurgical extraction and refining. ’Lower’ accessibility is in red, ‘moderate’ in orange, ‘higher’ in yellow, and not determinable in grey. The uncertainty ranking (data quality ranking, DQR) is presented next to the result of each of the 48 operational section. In this ‘High’ stands for ‘high quality’, ‘Fair’ stands for ‘fair quality’, and ‘Poor’ stands for ‘poor quality’. N/A stands for not available.

Sub-class	Component	Sub-component	Indicator	Country	Collecting	DQR	Manual and mechanical processing	DQR	Metallurgical extraction	DQR	Refining	DQR
Availability	Geological knowledge	Quantity	Annual mass flow	Switzerland, manual processing	🟥	1.8 Fair	🟥	1.8 Fair	⬜	0 N/A	⬜	0 N/A
				Switzerland, mechanical processing				1.8 Fair	⬜	0 N/A	⬜	0 N/A
				Japan			No process		🟥	3.9 Poor	🟥	3.9 Poor
				Germany					🟥	3.9 Poor	🟥	3.9 Poor
				Austria					🟥	3.9 Poor	🟥	3.9 Poor
				Vietnam					🟥	3.9 Poor	🟥	3.9 Poor
		Quality	Mass fraction	Switzerland	🟥	1.9 Fair	🟨	1.9 Fair	⬜	0 N/A	⬜	0 N/A
				Japan			No process		⬜	3.9 Poor	⬜	3.9 Poor
				Germany					⬜	3.9 Poor	⬜	3.9 Poor
				Austria					⬜	3.9 Poor	⬜	3.9 Poor
				Vietnam					⬜	3.9 Poor	⬜	3.9 Poor
	Eligibility	Market concentration	Market concentration	Switzerland	🟨	1.6 Fair	🟨	1.6 Fair	⬜	0 N/A	⬜	0 N/A
				Japan			No process		⬜	0 N/A	⬜	0 N/A
				Germany					⬜	0 N/A	⬜	0 N/A
				Austria					⬜	0 N/A	⬜	0 N/A
				Vietnam					⬜	0 N/A	⬜	0 N/A
		Regulatory requirement	Operating license	Switzerland	🟨	1.0 High	🟨	1.0 High	⬜	0 N/A	⬜	0 N/A
				Japan			No process		🟨	1.8 Fair	🟨	1.8 Fair
				Germany					🟨	1.8 Fair	🟨	1.8 Fair
				Austria					🟨	1.8 Fair	🟨	1.8 Fair
				Vietnam					🟨	1.8 Fair	🟨	1.8 Fair
Approachability	Technology	Knowledge of machine and infrastructure	Knowledge of machine and infrastructure	Switzerland	🟨	1.6 Fair	🟥	1.6 Fair	🟥	3.0 Fair	🟥	3.0 Fair
				Japan			No process		🟨	3.0 Fair	🟨	3.0 Fair
				Germany					🟨	3.0 Fair	🟨	3.0 Fair
				Austria					🟨	3.0 Fair	🟨	3.0 Fair
				Vietnam					🟨	3.0 Fair	🟨	3.0 Fair
		Use of machine and infrastructure	Indexed annual rate of collection, mining recovery and processing recovery	Switzerland, manual processing	🟧	2.6 Fair	🟨	2.5 Fair	⬜	0 N/A	⬜	0 N/A
				Switzerland, mechanical processing			🟥	2.5 Fair	⬜	0 N/A	⬜	0 N/A
				Japan			No process		🟨	3.9 Poor	🟨	3.9 Poor
				Germany					🟨	2.6 Fair	🟨	2.6 Fair
				Austria					🟨	2.6 Fair	🟨	2.6 Fair
				Vietnam					🟨	2.6 Fair	🟨	2.6 Fair
	Economy	Cost for collecting, mining and processing	Indexed costs in a country	Switzerland, manual processing	🟧	1.6 Fair	🟥	2.0 Fair	⬜	0 N/A	⬜	0 N/A
				Switzerland, mechanical processing			🟨	2.0 Fair	⬜	0 N/A	⬜	0 N/A
				Japan			No process		⬜	0 N/A	🟥	2.8 Fair
				Germany					⬜	0 N/A	🟥	2.6 Fair
				Austria					⬜	0 N/A	🟥	2.6 Fair
				Vietnam					⬜	0 N/A	🟨	2.8 Fair
		Cost volatility	Indexed cost volatility in a country	Switzerland, manual processing	🟧	3.0 Fair	🟧	2.0 Fair	⬜	0 N/A	⬜	0 N/A

Sub-class	Component	Sub-component	Indicator	Country	Collecting	DQR	Manual and mechanical processing	DQR	Metallurgical extraction	DQR	Refining	DQR
		for collecting, mining and processing		Switzerland, mechanical processing			🟧	2.0 Fair		0 N/A		0 N/A
				Japan			No process			0 N/A	🟨	2.8 Fair
				Germany						0 N/A	🟧	2.6 Fair
				Austria						0 N/A	🟨	2.6 Fair
				Vietnam						0 N/A	🟧	2.8 Fair
	Society	Human rights implications	Freedom of speech	Switzerland	🟨	1.6 Fair	🟨	1.6 Fair		0 N/A		0 N/A
				Japan			No process		🟨	1.6 Fair	🟨	1.6 Fair
				Germany					🟨	1.6 Fair	🟨	1.6 Fair
				Austria					🟨	1.6 Fair	🟨	1.6 Fair
				Vietnam					🟥	1.6 Fair	🟥	1.6 Fair
		Societal stability	Political stability	Switzerland	🟨	1.6 Fair	🟨	1.6 Fair		0 N/A		0 N/A
				Japan			No process		🟨	1.6 Fair	🟨	2.4 Fair
				Germany					🟨	1.6 Fair	🟨	1.6 Fair
				Austria					🟨	1.6 Fair	🟨	1.6 Fair
				Vietnam					🟥	2.4 Fair	🟥	2.4 Fair
	Environment	Environmental regulations requirement	Environmental regulations and standards	Switzerland	🟨	1.0 High	🟨	1.0 High		0 N/A		0 N/A
				Japan			No process		🟨	3.0 Fair	🟨	3.0 Fair
				Germany					🟨	1.6 Fair	🟨	1.6 Fair
				Austria					🟨	1.6 Fair	🟨	1.6 Fair
				Vietnam					🟥	5.0 Poor	🟥	5.0 Poor
		Total environmental impacts	ReCiPe end point value: Ecosystems and Human health	Switzerland, manual processing	🟨	1.0 High	🟨	1.0 High		0 N/A		0 N/A
				Switzerland, mechanical processing			🟨	1.0 High		0 N/A		0 N/A
				Japan			No process			0 N/A		0 N/A
				Germany						0 N/A		0 N/A
				Austria						0 N/A		0 N/A
				Vietnam						0 N/A		0 N/A

Table 24: The results of the accessibility evaluation related to mining deposits in the geosphere (MDG). The scoring bases on ore in 2015 along the operational steps: collecting, manual and mechanical processing, metallurgical extraction and refining. 'Lower' accessibility is in red, 'moderate' in orange, 'higher' in yellow, and not determinable is in grey. The uncertainty ranking (data quality ranking, DQR) is presented next to the result of each of the 48 operational section. In this 'High' stands for high 'high quality', 'Fair' stands for 'fair quality', and 'Poor' stands for 'poor quality'N/A stands for not available.

Sub-class	Component	Sub-component	Indicator	Country	Mining	DQR	Mineral processing	DQR	Metallurgical extracting	DQR	Refining	DQR
Availability	**Geological knowledge**	Quantity	Annual mass flow	Australia / Malaysia	🟧	1.0 High	🟧	1.6 Fair	🟧	1.6 Fair	🟧	1.6 Fair
				China	🟨	2.9 Fair	🟨	1.8 Fair	🟨	1.8 Fair	🟨	1.8 Fair
				USA	🟥	1.6 Fair	🟥	1.8 Fair	🟥	1.8 Fair	🟥	1.8 Fair
		Quality	Mass fraction	Australia / Malaysia	🟨	2.8 Fair	🟧	2.4 Fair	⬜	2.8 Fair	⬜	2.3 Fair
				China	🟧	2.8 Fair	🟧	1.9 Fair	⬜	2.8 Fair	⬜	2.3 Fair
				USA	🟨	2.8 Fair	🟥	2.4 Fair	⬜	2.8 Fair	⬜	2.3 Fair
	Eligibility	Market concentration	Market concentration	Australia / Malaysia	🟨	1.9 Fair	🟨	1.9 Fair	🟨	1.9 Fair	🟨	1.9 Fair
				China	🟥	1.9 Fair	🟥	1.9 Fair	🟥	1.9 Fair	🟥	1.9 Fair
				USA	🟨	1.9 Fair	🟨	1.9 Fair	🟨	1.9 Fair	🟨	1.9 Fair
		Regulatory requirement	Operating license	Australia / Malaysia	🟨	2.5 Fair	🟨	2.5 Fair	🟨	2.5 Fair	🟨	2.5 Fair
				China	🟨	2.8 Fair	🟨	2.8 Fair	🟨	2.8 Fair	🟨	2.8 Fair
				USA	🟨	2.4 Fair	🟨	2.5 Fair	🟨	2.5 Fair	🟨	2.5 Fair
Approachability	**Technology**	Knowledge of machine and infrastructure	Knowledge of machine and infrastructure	Australia / Malaysia	🟨	2.4 Fair	🟨	2.4 Fair	🟨	2.4 Fair	🟨	2.4 Fair
				China		2.5 Fair		2.5 Fair		2.5 Fair		2.5 Fair
				USA		1.9 Fair		1.9 Fair		1.9 Fair		1.9 Fair
		Use of machine and infrastructure	Indexed annual rate of collection, mining recovery and processing recovery	Australia / Malaysia	🟨	4.3 Poor	🟨	3.3 Poor	🟨	3.3 Poor	🟨	3.3 Poor
				China	🟨	4.1 Poor	🟧	3.3 Poor	🟧	3.3 Poor	🟨	3.3 Poor
				USA	🟨	4.3 Poor	🟨	3.3 Poor	🟨	3.3 Poor	🟨	3.3 Poor
	Economy	Cost for collecting, mining and processing	Indexed costs in a country	Australia / Malaysia	⬜	0 N/A	🟧	4.0 Poor	🟨	3.4 Poor	🟥	2.4 Fair
				China	⬜	0 N/A	🟨	4.0 Poor	🟨	3.5 Poor	🟨	3.4 Poor
				USA	⬜	0 N/A	🟧	4.0 Poor	🟥	3.4 Poor	🟥	2.4 Fair
		Cost volatility for collecting, mining and processing	Indexed cost volatility in a country	Australia / Malaysia	⬜	0 N/A	⬜	0 N/A	🟧	3.9 Poor	🟨	1.9 Fair
				China	⬜	0 N/A	⬜	0 N/A	🟧	3.9 Poor	🟨	2.0 Fair
				USA	⬜	0 N/A	⬜	0 N/A	🟧	3.9 Poor	🟨	1.9 Fair
	Society	Human rights implications	Freedom of speech	Australia / Malaysia	🟨	1.8 Fair	🟨	1.8 Fair	🟧	1.8 Fair	🟧	1.8 Fair
				China	🟥	1.8 Fair	🟥	1.8 Fair	🟥	1.8 Fair	🟥	1.8 Fair
				USA	🟨	1.8 Fair	🟨	1.8 Fair	🟨	1.8 Fair	🟨	1.8 Fair
		Societal stability	Political stability	Australia / Malaysia	🟨	1.8 Fair	🟨	1.8 Fair	🟧	1.8 Fair	🟧	1.8 Fair
				China	🟥	1.8 Fair	🟥	1.8 Fair	🟥	1.8 Fair	🟥	1.8 Fair
				USA	🟧	1.8 Fair	🟧	1.8 Fair	🟧	1.8 Fair	🟧	1.8 Fair
	Environment	Environmental regulations requirement	Environmental regulations and standards	Australia / Malaysia	🟨	1.0 High	🟨	1.0 High	🟨	1.0 High	🟨	1.0 High
				China	🟥	5.0 Poor	🟥	5.0 Poor	🟥	5.0 Poor	🟥	5.0 Poor
				USA	🟨	4.1 Poor	🟨	4.1 Poor	🟨	4.1 Poor	🟨	4.1 Poor
		Total environmental impacts	ReCiPe end point value: Ecosystems and Human health	Australia / Malaysia	⬜	0 N/A	⬜	0 N/A	⬜	0 N/A	⬜	0 N/A
				China	🟨	1.8 Fair	🟨	1.8 Fair	🟨	1.8 Fair	🟨	1.8 Fair
				USA	⬜	0 N/A	⬜	0 N/A	⬜	0 N/A	⬜	0 N/A

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6.6 Concluding discussion

6.6.1 Summary of findings

In this Chapter, a framework was presented that characterises and evaluates the accessibility of raw materials from EoL products and the Earth's crust under sustainability considerations. This framework was developed in three sections: framework refinement, confirmation and consolidation, and application with characterisation and evaluation.

6.6.1.1 Framework refinement, confirmation and consolidation

The selected sub-components and indicators were refined and confirmed with 58 experts in round I and 48 experts in round II of the Delphi study. More important sub-components and indicators by statistical methods were identified by statistical methods; however, the consensus establishment of the sub-components and indicators was limited. Similarly, in life cycle assessments, a field that has 20 years of research, there is limited agreement on which indicator to use for evaluating metallic raw materials (Klinglmair, Sala and Brandão, 2014; Drielsma *et al.*, 2016).

It should be noted that the developed framework might require refinement. The included components were identified through literature review and concept extraction in Chapter 5. This means other researchers reviewing the literature might have considered other components. For example, a framework that includes a three sustainability components, respectively pillars, are society, economy and environment (Pojasek, 2010). This three pillar framework is similar to these suggestions but clearly differs by not including technology and knowledge on material and certainty explicitly (geological knowledge).

6.6.1.2 Characterization of raw material accessibility

The results of the application showed that Nd_2O_3 was characterised of both sources: the EoL products (MDA) and the Earth's crust (MDG). Specifically, this characterisation demonstrated Nd_2O_3 is accessible from the Earth's crust deposits, but currently not from the anthropogenic deposit with HDDs in desktop PCs and laptops.

Characterizing the accessibility evaluation framework requires management of an extensive amount of information, which has to be collected and reviewed. For each component, sub-component and indicators, relevant information from diverse and heterogeneous sources needs to be synthesized and summarized.

I was further able to characterise a raw material, i.e. Nd_2O_3, with little available data from a broad perspective. To develop policies for government, both a general statement and a more in-depth statement on accessibility can be deduced. The more general statement could include information regarding **operating license**, **knowledge of machine and infrastructure** and **environmental regulations and standards**. The more in-depth statement could include information regarding **quantity**, **quality**, **use of machine and infrastructure**, **costs**, **freedom of speech**, **political stability** and the **total environmental impacts**. This is a clear distinction to research on similar evaluation approaches that focus more in a system level such as the UNFC (United Nations, 2013).

6.6.1.3 Evaluation of raw material accessibility

The results of the application showed that it is possible to evaluate, and with this compare, the accessibility of Nd_2O_3 at both sources: the EoL products (MDA) (Table 23) and the Earth's crust (MDG) (Table 24). Overall the accessibility level depends on the sourcing country for the components 'eligibility', 'economy', 'society' and 'environment'. In contrast, the components 'geological knowledge' and 'technology' depend on the global knowledge available.

Specifically, most of the operational steps were able to be evaluated but not all, since the data availability was low. Out of the 6 components and 4 operational steps for MDA and MDG, 39 operational sections of a total from 48 operational sections were able to be evaluated. These scored results constitute a condensed and versatile display of information, which provides a broad basis for establishing priorities or identifying hotspots for improvements for strategic decision making. Potential for improvements of both deposits were identified, namely (i) the 'geological knowledge' for EoL products, (ii) 'eligibility' particularly for the Earth's crust deposits with the highest **market concentration** for China, (iii) the 'technology' demonstrated as 'lower' during mechanical processing of the HDDs, (iv) the 'economy' showed for both MDA and MDG as 'lower' in the developed countries, particularly during metallurgical extraction and refining, and (v) 'society' and 'environment' resulted for both MDA and MDG as 'lower' in developing countries, particularly during metallurgical extraction and refining. Future mining of HDDs has shown that the resource might not be available and approachable. The availability might be hindered due to (i) increase in SDD use. (ii) The approachability might be hindered, since technological advancement during manual and mechanical processing is required, and (iii) currently non existent processing channels. The sustainability of mining activities was also investigated, and these results indicate a bipolar situation between developing and developed countries.

For the purpose of evaluating an early project development stage, providing a transparent and an easily adaptable methodological framework, the results were not aggregated to a single result. In contrast to this methodological framework, many availability evaluation studies performed a weighting or aggregation (NRC, 2008; Graedel *et al.*, 2012; EC, 2017a; Mateus *et al.*, 2017). Instead, the individual results of the 13 indicators were used to establish an accessibility evaluation of raw materials at an early project development stage. Nevertheless, implicitly weighting and scoring was performed by means of selecting components, sub-components and indicators.

6.6.2 Limitations

A challenge for any evaluation is related to the communicability and transparency of the results. To overcome this, these results were made available. Additionally, it is important to not only focus on the indicator results when providing the outcome, since indicators do not fully capture all information. Indicators tend to not account for the individual specificity and background (Merry, 2011). For instance, these indicators do not take into account each individual process operator or the local economic situation. To overcome the results transparency, it is important to provide additional relevant information such as references and assumptions.

A limitation of this accessibility evaluation is the focus on a single raw material in one evaluation. This is not a realistic situation, since the Nd_2O_3 is mined with other REE and neglects the influence of by-products. Therefore, it is central to consider the possibilities of by-product influence by providing clarifying comments on the final characterised and evaluated results. For instance, the REE from the Bayan Obo deposit were first mined as a by-product and many other deposits could commence mining of REE as a by-product rapidly (Goodenough, Wall and Merriman, 2017). Yet, evaluating individual raw materials can show possible supply shortages of several raw materials and then describe the influences among raw materials. For instance, cobalt-based magnets have been used to substitute Nd-magnets (Ueberschaar and Rotter, 2015). Additionally, it is not possible to identify common issues from different raw material sources. For example in the MDA, the component ‘geological knowledge’ resulted in ‘lower’ accessibility. This means there is a lack of information. This lack of information is now being addressed from many EU projects such as the ProSUM (Huisman *et al.*, 2016).

6.6.3 Implications

This accessibility evaluation is a positive step in enhancing the understanding of, and providing a solution towards, raw material issues. The framework expands the existing understanding of the concept of raw material availability by approachability. Both availability and approachability are united in accessibility. This understanding of availability investigation is comprised of ‘geological knowledge’ and ‘eligibility’. This investigation is among the few studies that include ‘geological knowledge’. No other study has investigated ‘eligibility’ according to the literature reviewed. This understanding of approachability focuses on addressing ‘technology’ and ‘economy’ in addition to ‘society’ and ‘environment’. So far little quantification has been carried out regarding ‘technology’.

This research’s strengths are in investigating the supply chain and waste management at different operational steps on the basis that it becomes possible to develop action plans for each operational step. In numbers, it becomes possible to identify 48 issues at the operational steps that could lead to 48 different actions. In this way, this framework differentiates to criticality evaluations that show one score along the operational steps. Additionally, this framework differs from the UNFC classification, which provides a descriptive final result that includes masses.

This research's limitation is the data certainty. This can be overcome by stating assumptions and ensuring this is taken into account while developing strategies for more detailed investigations. Consequently, with this framework, suggestions for detailed investigations of the 48 different possible actions can be made, thus the results should be considered as indicative.

6.6.4 Recommendations

The accessibility evaluation framework can be used as a tool to evaluate an early-project development stage in cases with little available data. This framework ensures an implementation of a broad sustainability perspective and also in identifying potential for further improvements, which implementation would need very little financial resources. This framework solely provides an indication about the current situation. This indication could support the prospection phase of MDG, which develops a first understanding of knowledge of material source and certainty, socio-economy, and project feasibility (Chapter 5). Additionally, this framework can be a solid basis for performing a broad pre-study for more in-depth evaluation by means of UNFC classification, criticality studies (UNFC, 2010; Bach *et al.*, 2017; Mateus *et al.*, 2017) or specific operational step improvements. In detail, this accessibility evaluation framework could support the UNFC classification framework with important information. The component 'geological knowledge' with the sub-components **mass** and **mass fraction** could provide basic information for the prospection phase and with this the UNFC axis geological knowledge. The component 'technology' with the sub-components **knowledge of machine and infrastructure** and **use of machine and infrastructure** could provide basic information for the UNFC axis field project status and feasibility. The other components, 'eligibility' with the sub-components **market concentration** and **regulatory requirement**, economy with the sub-components **costs for collecting, mining and processing** and **cost volatility for collecting, mining and processing**, 'society' with **working conditions**, **human rights implications**, **societal stability** and environment with the sub-components **environmental regulatory requirement** and **total environmental impacts** could provide fundamental knowledge for the UNFC axis the economic and social viability.

The application of this framework on several raw materials can not only increase this knowledge about the accessibility of raw materials, but also contribute to a broad early project development stage evaluation, identification of knowledge gabs, informed policy or business recommendations and an overview of the related possibilities and risks, which can help in strategic decision-making.

This could be used for instance to further develop indicators to determine the advancements towards a green economy, which is a priority research topic in the Swiss research concept from 2017-2020 (BAFU, 2016).

6.6.5 Further development

The results of this accessibility evaluation showed different methodological advancement potentials: (i) the evaluation could be further developed to a systematic procedure as applied for LCA with the ISO 14001 (ISO, 2010); (ii) the cost volatility largely depends on the studied year, since the REE supply recently faced a crisis (Sprecher *et al.*, 2017). Thus, it is important to investigate the costs in a dynamic manner; (iii) the data certainty implementation could be refined with a Monte Carlo simulation (Wittmer, Dominic, 2006; Graedel et al., 2012; Winterstetter et al., 2016a); (iv) the development of the framework application to corporations and regions, other EoL products with limited data such as PC, or EoL vehicles; or different Earth's crust deposits; (v) investigations of the little researched operational steps in more detail (Nansai *et al.*, 2017), particularly for metallurgical extraction and refining; and (vi) the investigation of the operational steps could profit from analysing the influence of different metals with each other as recommended by Nuss and Eckelman (2014).

6.6.6 Concluding statement

Overall, this chapter demonstrated the accessibility of raw material is quantifiable to provide important information about the early project development stage under sustainability considerations. This evaluation comprises a broad spectrum based on systematically selected sub-components and indicators for both MDA and MDG. This can contribute to a more uniform evaluation of raw materials. This framework can be applied to assist local and national governments in identifying knowledge gaps, hotspots, opportunities, risks and potentials for further investigation that can support informed policy or business recommendations to ensure long-term accessibility to raw materials.

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Chapter 7 Discussion and conclusions

This chapter provides the discussion, conclusions and recommendations, and future research. It is structured as these three sections. The first section includes a discussion of this thesis, then potential benefits and research limitations. The second section includes conclusions and recommendation. The final section includes four potential future research topics to round off this thesis.

7.1 Discussion

7.1.1 Summary

There are increased risks to the supply of scarce metals and concerns about the resource efficiency, because of the currently unclosed of material cycles. To reduce the risks to supply, the over two hundred years of comprehensively evolved approaches from MDG take a systematic approach in exploring a deposits. Consequently, for MDA similar approaches are needed as in MDG. (Brunner, 2011; Rankin, 2011; Wäger, Widmer and Stamp, 2011; Arndt and Ganino, 2012; Simoni, 2012; UNEP, 2012; Krook and Baas, 2013; Haines *et al.*, 2014). Therefore, a knowledge base that supports approaches for material recovery from the anthroposphere needs to be established, particularly in relation to scarce metals (Velis and Brunner, 2013), availability (Graedel and Reck, 2015), and accessibility (Eurometaux, 2010). To evaluate scarce metals, both prerequisites for recovery, namely availability and accessibility, need to be understood. Whilst availability is already well understood, accessibility is less well studied. Consequently, there is a need to investigate what accessibility means and how it is instructive in order to develop an accepted and utilisable prerequisite for recovery. To address this need, the aim of this thesis was to develop an interdisciplinary and structured methodological framework for characterising and evaluating the accessibility of scarce metals from end of life products and the Earth's crust under sustainability considerations.

7.1.1.1 Chapter 2: Literature review

To set the scene for this research, a literature review was carried out that informed in the following findings and gaps in scientific knowledge.

(i) Approaches for evaluating the mining of the geosphere and anthroposphere
  - Finding I: over 200 years evolved geological mining approaches that can be related to the UNFC classification framework for evaluating MDG comprise: conceptual and surface study through UNFC G-axis at an early project development stage.
  - Finding II: correlated approaches for evaluating MDA comprise conceptual and surface studies with MFA at an early project development stage. However, there is a lack of systematic approaches in MDA as applied for MDG.

- Gap in scientific knowledge: during the early project development stage, there is need to fill the knowledge gap of developing a structural approach to geologically characterise and evaluate MDA from EoL products (Stamp, 2014; Velis and Brunner, 2013). This is addressed with the research aim (i) and Chapter 4.

(ii) Approaches for evaluating the prerequisites for recovery: availability and accessibility

- Finding I: 16 geological and supply chain evaluation approaches are available to raw material availability; no existing evaluation approach regarding accessibility.
- Finding II: 6 components, 21 sub-components, and 26 indicators could be used to investigate accessibility.
- Gaps in scientific knowledge: there is a need to investigate accessibility by means of linguistic methods, inputs from experts, and practical applications. This supports the development of a more resilient, robust and interdisciplinary methodological framework for raw material management (adopted from Velis and Brunner, 2013; Hagelüken, 2014). This is addressed through the work presented in Chapter 5 and Chapter 6, which, respectively, are research objectives (ii), (iii).

7.1.1.2 Chapter 3: Research methodologies

To ensure the most fitting method was applied for this research, different methods were reflected, which resulted in following findings.

(i) Methodology for Chapter 4

- Finding I: focus group was selected to meet the requirements for a structured brainstorming process for the framework development, as this method enables the creative potential of each expert.
- Finding II: Delphi technique was selected to meet the requirements, as the participating experts have limited influence over each other.

(ii) Methodology for Chapter 5

- Finding I: the ‘concept extraction’ addresses this study’s research objective (ii) of building the fundamental knowledge of ‘accessibility’.

(iii) Methodology for Chapter 6

- Finding I: Delphi technique is the most suited method for framework refinement and confirmation, as it is easy to coincide in time and space, easier to build groups of experts with the optimal participation number, ensures anonymity, and limited influence among the individual experts.

7.1.1.3 Chapter 4: A geological reconnaissance of electrical and electronic waste as a source for rare earth metals

Before discussing the potential benefits and research limitations of this research, the following states the aim, followed by the respective key results, discussions and a statement on the achievement of the research aim.

Aim: Develop a structured approach for a reconnaissance of anthropogenic deposits by means of geological characterisation and evaluation.

Summary of results and discussions:

- A framework connecting the statuses and processes of the geosphere with the anthroposphere.
- Analogies between processes in geosphere and anthroposphere.
- A 'geological setting' characterisation and evaluation of three REE EoL products.
- The results of the concentration – dilution profile has proven useful to highlight the location of the most concentrated anthropogenic deposits. For instance the most concentrated deposits were i) at the recyclers for the case studies electric car with Nd and fluorescent lamp with Eu; ii) at the user for the fibre optic cable with Er.
- The anthropogenic deposits of Neodymium-Iron-Boron permanent magnets and fibre optic cable with Er (Angerer, 2009a) are expected to grow for at least the next 20 years, which is more than the current estimate of 20 years mine life of the Mt. Weld geological deposit (Hoatson, Jaireth and Miezitis, 2011).
- Mining the REE held in these so-called 'anthropogenic deposits' is likely to involve considerably fewer social and environmental impacts than the extraction from the present major mined, geological deposits (Alonso *et al.*, 2012). These geological deposits often contain accumulations of radioactive thorium and uranium (Hoatson, Jaireth and Miezitis, 2011).
- Considering the high mass fractions, long mine life and fewer social and environmental impacts with the expected supply constraints of Nd (Roelich *et al.*, 2014) and Eu (USDOE, 2011), which both have limited or no substitution options (Graedel *et al.*, 2013), it is important to develop strategies and a common platform between mining of the geosphere and anthroposphere.

Statement: Research aim (i) was achieved.

7.1.1.4 Chapter 5:A framework for evaluating the accessibility of raw materials from end-of-life products and the Earth's crust

Before discussing the potential benefits and research limitations of this research, the following states the aim, followed by the respective key results, discussions and a statement on the achievement of the research aim.

Aim: Build fundamental knowledge, develop and initially apply a framework for characterising and evaluating accessibility for both EoL products and the Earth's crust.

Summary of results and discussions:

- A systematic investigated use of fundamental terms: accessibility, availability, and approachability by means of quantitative linguistic research methods.
- The text analysis suggests that 'accessibility' and 'availability' are not yet established terms in the literature. Only Tiess (2011) was found to distinguish clearly between accessibility to, and availability of, minerals in the context of exploration and policy development.
- The semantic analysis of the EC corpus revealed that accessibility was strongly collocated to 'measure' and 'indicator', which indicates that an evaluation should include indicators and be measureable.
- The conceptualisation of accessibility played a major role in urban planning research (Klaesson, Larsson and Norman, 2015). This urban planning conceptualisation dates back to work undertaken by Hansen (1959) (Karlsson and Gråsjö, 2013), are widely applied, and is based on the physical law of gravitation (Klaesson, Larsson and Norman, 2015).
- A novel and consistent framework for evaluating the supply of raw materials on system level, i.e. accessibility evaluation framework.
- This framework provides an indication about the current supply situation rather than a detailed assessment. This indication could particularly support the prospection phase, which aims to develop knowledge on type, location, volume, legislation, technology and costs (Winterstetter *et al.*, 2016b)
- The insights gained from the application of this framework could provide important information to support a UNFC classification.
- Demonstration of the utility from the developed framework by evaluating the raw material supply of four REE case studies. These case studies consist of REE sourced from the deposits: EoL phosphor of fluorescent lamps with Eu, Switzerland; EoL drive

motor of electric car with Nd, Switzerland; EoL fibre optic cable with Er, Switzerland; and Earth's crust Mt. Weld with Eu, Nd, Er, Australia / Malaysia.

- Perhaps unexpectedly, the currently mined Mt. Weld deposit generates an 'approachability' outcome of medium to high, because the quantified societal and environmental impacts associated with processing in Malaysia require the same level as European standards.
- There are two constraints on this aggregated evaluation, namely that the different components are not apparent and that the current evaluation is static.

Statement: Research aim (ii) was achieved.

7.1.1.5 Chapter 6: Evaluating the accessibility of raw metals from end-of-life products and the Earth's crust under sustainability considerations: methodological framework refinement, confirmation, consolidation and application

Before discussing the potential benefits and research limitations of this research, the following states the aim, followed by the respective key results, discussions and a statement on the achievement of the research aim.

Aim: Refine, confirm, consolidate and apply a structured methodology for characterising and evaluating accessibility for both EoL products and the Earth's crust.

Summary of results and discussions:

- A refined and consistent methodological framework by means of Delphi survey with a total of 48 consolidated expert judgements. This investigation resulted in a framework with 6 components, 13 sub-components, and 13 indicators (of which 12 sub-components and indicators were applied).
- The consensus establishment of the sub-components and indicators was is limited. Similarly, in life cycle assessments, a field that has 20 years of research, there is limited agreement on which indicator to use for evaluating metallic raw materials (Klinglmair, Sala and Brandão, 2014; Drielsma *et al.*, 2016).
- I was further able to characterise a broad perspective of a raw material, i.e. Nd_2O_3, with little available data. To develop policies for government, both a general statement and a more in-depth statement on accessibility can be deduced. The more general statement could include information regarding **operating license**, **knowledge of machine and infrastructure** and **environmental regulations and standards**. The

more in-depth statement could include information regarding **quantity**, **quality**, **use of machine and infrastructure**, **costs**, **freedom of speech**, **political stability** and the **total environmental impacts**. This is a clear distinction to research on similar evaluation approaches that focus more in a system level such as the UNFC (United Nations, 2013).

- For the purpose of evaluating an early project development stage, providing a transparent and an easily adaptable methodological framework, not to aggregate these results to a single result was chosen. In contrast to this methodological framework, many availability evaluation studies performed a weighting or aggregation (NRC, 2008; Graedel *et al.*, 2012; EC, 2017a; Mateus *et al.*, 2017). Nevertheless, implicitly a weighting and scoring was performed by means of selecting components, subcomponents and indicators.
- This research's strengths are in investigating the supply chain and waste management at different operational steps on the basis that it becomes possible to develop precise action plans for each operational step.
- Demonstration of the utility of the advanced framework through case studies of REEs sourced from the deposits: EoL HDDs in desktop PCs and laptop with Nd from Switzerland; and the Earth's crust with Nd from China, Australia / Malaysia and the USA.
- This research's limitation is the data certainty. This can be overcome by stating assumptions and ensuring this is taken into account while developing strategies for more detailed investigations.
- The accessibility evaluation framework can be used as a tool to evaluate an early-project development stage in cases with little available data. This ensures an implementation of a broad sustainability perspective and also in identifying potential for further improvements, which implementation would need very little financial resources.
- This framework solely provides an indication about the current situation. This indication could support the prospection phase of MDG, which develops a first understanding of knowledge of material source and certainty, socio-economy, and project feasibility (Chapter 5).
- This framework can be a solid basis for performing a broad pre-study for more in-depth evaluation by means of UNFC classification, criticality studies (UNFC, 2010; Bach *et al.*, 2017; Mateus *et al.*, 2017) or specific operational step improvements.

Statement: Research aim (iii) was achieved.

The original contribution and significance of this research can be summarised as follows:

- The novel characterisation of the ‘geological setting’ of three MDA case studies (Chapter 4).
- The evaluation of the geological setting of three MDA by means of UNFC framework (Chapter 4).
- The novel application of quantitative linguistic methods for framework development regarding raw material management (Chapter 5).
- The novel perspective of raw material management, by means of raw material accessibility, which is semantically at the intersection of raw material availability and approachability (Chapter 5 and Chapter 6).
- The novel and broad use of a sustainability consideration that includes: geological knowledge, eligibility, technology, economy, society, and environment (Chapter 5 and Chapter 6).
- A newly developed, refined and confirmed accessibility evaluation framework that is based on the same set of indicators to characterise and evaluate both MDA and MDG during an early project development stage (Chapter 5 and Chapter 6).
- The novel characterisation and evaluation of scarce metal oxides from EoL products and the Earth’s crust along the supply chain and waste management (Chapter 5 and Chapter 6).

7.1.2 Potential benefits of the developed methodological framework: accessibility evaluation

7.1.2.1 The application of (semi-) quantitative indicators

The framework is a tool for governments to better understand the accessibility of scarce metals at an early project development stage. For this, 12 applied indicators enable a (semi-) quantitative characterisation and evaluation of the raw material supply and waste management that can support decision-making (Chapter 6). Additionally, by integrating sustainability considerations, the information from the methodological framework is relevant to and supports the long-term raw material supply as anticipated by both British and Swiss governments (BAFU, 2016; UK Research Council, 2016). The methodological framework also offers a standardised approach for benchmarking different raw materials against key performance indicators, such as **annual mass flow**, **market concentration**, and **indexed recovery rate**. This will aid in further development of policies in the context of complex raw material supply and waste management by highlighting hotspots for in-depth investigations. One such policy is the currently revised ‘Ordinance on the Return, Take-Back and Disposal of Electrical and Electronic Equipment’ (FOEN, 2013) or the development of indicator towards a green economy (BAFU, 2016).

7.1.2.2 The complementation of the UNFC classification framework

The literature review on discussing the UNFC classification for an early project development stage in section 2.3 resulted in three major observations: (i) in the UNFC classification explicit indicators, apart from quantity, are not used; (ii) the UNFC class 'geological knowledge' is considered relevant for reconnaissance evaluation, e.g. Winterstetter, (2016), and (iii) the sustainability considerations of society and environment are currently being integrated to the UNFC (UNFC, 2017a, b, d). Focusing on the 'geological knowledge' during an early project development stage and not including broad sustainability considerations evidently limits the overall statement. For these reasons, an alternative methodological framework was developed in this PhD research. Due to the inclusion of (i) explicit indicators, (ii) utilising components that include 'geological knowledge', and (iii) applying a broad sustainability perspective, it was possible to overcome the limitation with a broad characterising and evaluative overall statement. Additionally, because the framework was developed in line with the systematic UNFC classification framework regarding the use of classes and sub-classes in Chapter 6, the results from the accessibility characterisation and evaluation complement the UNFC classification. Overall, the research results shown in this thesis demonstrate the usefulness of the accessibility framework for complementing the UNFC classification framework with specific indicators utilising classes and sub-classes.

7.1.2.3 The use of the methodological framework: accessibility evaluation

The characterisation and evaluation of the methodological framework supports governments in achieving their ambitions: (i) to develop and refine indicators toward a green economy and (ii) securing the supply of materials, respectively energy (BAFU, 2016; UK Research Council, 2016). Additionally, the accessibility evaluation can provide an indication for in-depth investigation on the 'proportional' effort to recover scarce metals (FOEN, 2013). Whilst the framework has been developed for raw material sources from the Swiss, Chinese, Australian / Malaysian, and USA contexts, it could be applied in many other countries to support the development of a green economy and investigate potentials for in-depth investigation on recovering scarce metals from technological equipment, such as WEEE (FOEN, 2013).

There has been little research investigating separately the different operational steps for securing the raw material supply from a broad sustainability perspective (Sprecher *et al.*, 2015). An example is the e-Recmet project (BAFU, 2015b); due to the detailed data availability regarding Nd_2O_3 recovery from HDDs this project was selected as a case study. This was complemented with three case studies regarding the extraction of Nd_2O_3 from Earth's crust deposits and its subsequent processing. Hence, the results of the framework provide insights on the accessibility situation along the operational steps, namely (i) collecting, and mining; (ii) manual and mechanical processing, and mineralogical processing; (iii) metallurgical extraction; and (iv) refining.

In addition to the research plan in 2012 by the Swiss government on developing a set of indicators for measuring the success toward a green economy (BAFU, 2012b), there is further need to research this topic by refining the indicators for a green economy (BAFU, 2016). This situation suggests that there is not yet a suitable set of indicators for measuring the success(es) of a green economy. Given the potential value provided from the requests in the Swiss research plan in 2012 and 2016, and the outcomes of this thesis, its application at the Swiss government level may be beneficial and would enable application of the analytical framework developed in this thesis.

7.1.3 Research limitations

In this PhD research, a methodological framework for investigating the accessibility of raw materials was developed that is based on 12 applied (semi-) quantitative indicators to support decision making within government. However, a number of limitations have been identified in the research methodology. Some limitations are discussed below.

7.1.3.1 The data availability and uncertainty

A key limitation of the research presented in this thesis concerns the availability and uncertainty of input data. First the data availability and then the data uncertainty are discussed.

Issues concerning data availability have been discussed particularly in Chapter 5 and Chapter 6. However, in Chapter 4 the data availability was not an issue and thus not discussed, as there was little data needed for the resulting descriptive and systematic geological reconnaissance. In Chapter 5 the data availability was limited but did not influence the outcome. This was for two reasons: (i) the applied characterisation was descriptive with qualitative and quantitative indicators, and (ii) the applied evaluation with a descriptive scoring was similar to the UNFC (United Nations, 2013). In Chapter 6, the data availability was much more limited and did slightly influence the research outcome. The characterisation is based on (semi-) quantitative indicators and the evaluation then based on a quantitative scoring, aiming to identify hotspots with potentials for further development regarding 'geological knowledge', 'eligibility', 'technology', 'economy', 'society' and 'environment'. Consequently, for framework development, case studies with enough available data were selected. Overall, this demonstrates that, for characterising and evaluating the accessibility, it is important that some data are available. Conversely, descriptive characterisation and evaluation is possible with very little available data, as with geological reconnaissance. This means, that depending on the focus of the investigation, whether descriptive or quantitative, the consequence of data availability can be greater or negligible.

Issues concerning data uncertainty have been discussed in Chapter 5 and Chapter 6. In Chapter 4, similarly to data availability, data uncertainty was not discussed, as it was out of scope. In Chapter 5 data uncertainty was investigated as a precursor for detailed future assessment. In Chapter 6 data uncertainty was taken into account by means of a data quality ranking (DQR) to each quantifiable data. The DQR is commonly used in material flow analysis (Turner, Williams and Kemp, 2015), life cycle assessment (Weidema and Wesnæs, 1996) and the geological availability assessment approach (Mateus *et al.*, 2017). The results of Chapter 6 showed the quality of the data sources were mainly poor to fair and only few high. This indicates that there is a lack of underlying quality data, especially regarding temporal and geographical relevance. These are recognised issues in the field of quantitative indicator development/application (Bach *et al.*, 2017). However, the deficiency of high quality data is a source of uncertainty among the accessibility results, as shown in this thesis. Consequently, it is central to consider the provided results as indicative rather than conclusive. This is particularly important; since the results of this thesis characterise and evaluate complex multifaceted interactions of a 'wicked' problem, see section 2.3.4, in which problems remain open-ended and inconclusive (Feiz and Ammenberg, 2017).

7.1.3.2 The context surrounding qualitative and quantitative indicators

The methodological framework was developed to characterise and evaluate accessibility based on qualitative and quantitative indictors in Chapter 5 and (semi-) quantitative indicators in Chapter 6. Whilst indicators can produce readily understandable and practical forms of information for decision-making, they tend to overlook the context surrounding indicators (Merry, 2011). For example, 'eligibility', as used in Chapter 6, consists of two indicators regarding **market concentration** and **operating license**. These indicators cover two aspects of 'eligibility' but not aspects regarding **WGI 'rule of law'** or **policy potential index**. Considering the two indicators **market concentration** and **operating license** only poses a risk of misleading, superficial or possibly wrong information in the overall outcome (Merry, 2011). The use of two complementary indicators was taken for three reasons: (i) indicators summarise complex, multi-dimensional realities; (ii) indicators can evaluate progress over countries and time; and (iii) indicators facilitate communication between stakeholders (Saltelli *et al.*, 2005). These reasons are fundamentally related to the aim of this rsearch, as outlined in section 1.2. Therefore, central aspects in this framework are the comparison of MDA and MDG among, different countries, and the support of government in decision-making in complex and multi-dimensional realities. To overcome the risks of applying indicators, it is critical to provide further relevant information (Feiz and Ammenberg, 2017). In Chapter 6, this is implemented by stating major assumptions while quantifying accessibility. This provides an important context for the indicators. However, a systematic description is limited in this thesis. Since this is a central issue, it is addressed in the future research section 7.3.

7.1.3.3 The Delphi survey with consensus establishment

As described in Chapter 6, the Delphi study was used to refine and confirm the sub-component and indicator selection of the accessibility evaluation. This part of the study had two aims: (i) establishing consensus among the surveyed experts and (ii) identifying statistically the relatively more important sub-components and indicators. The direction taken in this study was to use the well-researched coefficient Kendall's W., which resulted in low consensus after two Delphi study rounds. Nevertheless, there was more consensus after Delphi study round II. This use of the Kendall's W. coefficient contradicts studies that expect a high level of variability in the overall consensus establishment (Walters and Javernick-Will, 2015). The decision to use Kendall's W. coefficient was based on two principle reasons: (i) this coefficient is frequently applied and widely recognised as the best coefficient for ranking type Delphi studies (Okoli and Pawlowski, 2004); and (ii) the Kendall's W. coefficient method establishes an 'association between responses' rather than other more strict coefficients, which establish an 'agreement between responses'. However, the Kendall's W. coefficient still takes into account 'chance agreement' for investigations with >20 experts (Paré *et al.,* 2013). Furthermore, the means to establish consensus with the Kendall's W. coefficient in this thesis would have taken 5 or 6 additional Delphi study rounds, and would have lasted for about one or two years of additional research, as indicated by Tavana *et al.* (2012). Moreover, the second aim of the Delphi study of establishing statistically more important sub-components and indicators was fully achieved after two Delphi study rounds. Meijering, Kampen and Tobi (2013) provide evidence that it is common to achieve moderate consensus, and most studies are terminated after two rounds with moderate consensus in Delphi surveys.

7.1.3.4 The first step of developing a framework for characterising and evaluating the accessibility

In Chapter 4, as a preparation for the accessibility evaluation, a 'geological setting' characterisation and 'UNFC' evaluation was applied, in the context of geological reconnaissance on three case studies from MDA. In Chapter 5 the initially developed methodological framework in this thesis showed its utility with four case studies, one from MDG and three from MDA. In Chapter 6, the refined and confirmed framework demonstrated its utility with four case studies, one from MDA and three from MDG. For developing a novel framework, and to demonstrate the full utility, this presents a limited number of case studies. For instance, Graedel *et al.* (2012) applied their evaluation approach on 6 different metallic elements and alloys to show the full utility. In contrast, this evaluation was applied to REE and REO only. Consequently, this refined and confirmed methodological framework with 8 case studies take a first step, which should be applied further.

The initially developed framework and the applied case studies neglect influences that are important for mining deposits, such as the type of by-products or interconnected carrier metals (Verhoef, Dijkema and Reuter, 2004). Additionally, the refined and confirmed framework was developed while quantifying one output raw material, i.e. Nd_2O_3. Hence an application on the output of different raw materials may lead to advancement of the developed methodological framework (Nuss and Eckelman, 2014), since the accessibility to different raw materials can influence each other. Additionally, while gathering the data for different raw material sources in EoL products or Earth's crust and output raw materials, certain information may not be available or the quantification of a certain indicator, respectively scoring, might need further development. This can be exemplified with the advancement of the EU availability evaluation on critical raw material from 2014 to 2017 (EC, 2014, 2017a). The 2017 evaluation was refined and now integrates more indicators such as the 'import reliance' and 'import restrictions and trade agreement' (EC, 2014, 2017a). To better understand the wider effects of the refined and confirmed methodological framework, additional applications are suggested in the future research section 7.3.

7.2 Conclusions and recommendations

This thesis is concerned with the accessibility of raw materials, focusing on a national level, for the purposes of providing decision support to governments. The main conclusions and recommendations of this research are summarised in the following. The recommendations are for policy makers related to raw material management.

1) **Geological setting.**
   Conclusions: In general, the characterisation of the 'geological setting' characterisation and subsequent evaluation was found to provide a systematic and narrowing (from broad to specific) descriptive statement for investigating the raw material recovery states of MDA. In particular, describing the 'concentration-dilution profile', 'host rock', and raw material 'mineralization' with harmful substances, and 'current status' were found to demonstrate innovative and substantial benefits, and can be used as a first step of the 'evaluation steps' towards a proven resource. The description, however, depends on the defined scope of the study. This can consist of spatial scope, temporal scope or raw material selection.
   Recommendations: In Chapter 4, the need for the development of similar knowledge base for MDA as commonly used in MDG was addressed. In particular, both MDA and MDG require knowledge about mineable deposits (Lederer, Laner and Fellner, 2014; Winterstetter *et al.*, 2015). Since there is currently limited knowledge on MDA from a geological perspective, this makes it difficult to compare MDA with MDG and thus limits the perception of MDA as

an additional future resource. It is, therefore, suggested that a systematic geological deposit characterization of EoL products, landfills, building stocks or EoL vehicles is applied more consistently by local and national government authorities to develop an understanding on the anthropogenic resource deposits. Moreover, this would provide a first step in providing a 'proportional' effort to recover scarce metals as requested by the revision of the Swiss 'Ordinance on the Return, Take-Back and Disposal of Electrical and Electronic Equipment' (FOEN, 2013). The further development and use of the 'geological setting' is discussed further in the section future research 7.3.

2) **Data availability and uncertainty.**
   Conclusions: In Chapter 5 and Chapter 6, it is shown that there is limited high quality information along the operational steps, especially regarding the year and country of investigation. This represents a source of uncertainty in the accessibility evaluation, for which mostly secondary data was used. Given that the data collection often has an impact, particularly on the accuracy of the results (Graedel *et al.*, 2012), it is important to consider the outcomes of the accessibility framework as an indicative tool to support government decision making.
   Recommendations: There is generally a data uncertainty and a lack of available data, particularly regarding material prices and production costs along the operational steps. It is, therefore, strongly urged that the data availability and uncertainty is addressed by utilizing a recently developed knowledge base from projects such as ProSUM (www.urbanmineplatform.eu) (Huisman *et al.*, 2017) or MatCH (Gauch *et al.*, 2017). This potential is discussed further in the section future research 7.3.

3) **Complementation of the UNFC classification framework.**
   Conclusions: The applied accessibility evaluation framework could complement the UNFC classification framework at the reconnaissance evaluation stage. This complementation is important for three reasons: (i) during the reconnaissance evaluation, mainly the 'geological knowledge' is relevant (Winterstetter, 2016); (ii) the reconnaissance evaluation does not include broad sustainability considerations in alignment with the requests for sustainable development (Corder, McLellan and Green, 2010); and (iii) the social and environmental considerations of the UNFC are currently being revised (UNFC, 2017a, b, d).
   Recommendations: The results of Chapter 5 and Chapter 6 showed that the UNFC framework can be complemented by indicators and broad sustainability considerations during the reconnaissance evaluation. For this, it is recommended that there is further investigation and exchange with the UNFC working group on integrating sustainability considerations (UNFC,

2017a, b, d). Further research potential on more alignment with the UNFC can be found in the future research section 7.3.

4) **Possible lessons from situations scored with 'higher' accessibility.**

   Conclusions: The resulting level of 'higher' accessibility was found in both MDA and MDG. Important conclusions are provided in the following. In MDA, the 'eligibility' score (determined based on the indicator **market concentration)** in Switzerland was 'higher' accessibility. A low **market concentration** has already been described earlier by studies on WEEE management in Switzerland (Khetriwal, Kraeuchi and Widmer, 2009). In MDG, the results of 'technology' demonstrated as being a more experienced process than the results of 'technology' in MDA. This 'technology' was intensively developed during 1940 to 1960 (Gupta and Krishnamurthy, 2005). In MDG, the 'eligibility' results of some case studies demonstrated as 'higher' accessibility, i.e. 'lower' **market concentration** in Australia and USA, whereas China demonstrated as very clearly 'lower' accessibility, i.e. 'higher' **market concentration**. These findings of 'higher' accessibility can be used as a recommendation basis to improve the 'lower' accessibility findings.

   Recommendations: There is a need to develop a more robust and interdisciplinary methodological framework (adopted from Velis and Brunner, 2013; Hagelüken, 2014). The results of Chapter 6 showed that there are various potential lessons to develop a more robust framework but also to support a long-term accessibility to raw materials. Two potential lessons are discussed in the following: (i) regarding the component 'eligibility' with the indicator **market concentration**. This research showed in MDG, the current **market concentration** of REE is only a few producing countries worldwide, which poses a high supply risk. The high **market concentration** was highlighted as a challenge not only for the producing countries but also for the entire supply chain (Goodenough, Wall and Merriman, 2017). To ensure long-term accessibility to REE-containing products, it is important to consider the high **market concentration** of producing countries in relation with the global dependency of Chinese $Nd_2Fe_{14}B$ magnet production (Nansai *et al.*, 2017). (ii) The results for 'eligibility' and 'economy' demonstrated there is a discrepancy between price and **market concentration**. This discrepancy could be addressed by investigating the lessons from countries with 'higher' accessibility. It is, therefore, suggested that the 'higher' accessibility of 'eligibility' in Switzerland, could be proposed as a role model for the functioning of a system. This system is partly operated and systematically organized by the Swiss governmental body (Khetriwal, Kraeuchi and Widmer, 2009). Additionally, the discrepancy of 'economy' and 'eligibility' could be overcome by striving for supply contracts along the supply chain. For instance Lynas Corporation Ltd. entered a ten year supply contract with Japan (Lynas, 2010) and in this way guarantee a long-term purchaser for Lynas Corporation Ltd and supplier for Japan.

5) **Possible hotspots for improvements from situations scored with 'lower' accessibility.**
Conclusions: The outcome of this thesis can be used to provide (i) an indicator-based framework as an indication at early project stage toward a green economy (BAFU, 2016) and (ii) a knowledge base at an early project development stage toward securing the supply of material, respectively energy (BAFU, 2016; UK Research Council, 2016) through investigating the different levels of accessibility, i.e. 'lower', 'moderate', and 'higher'. In particular, the results of 'lower' accessibility indicate that, in order to secure the supply of the material, respectively energy, there is need to address the 'lower' accessibility at a national level and provide actions to ensure the long-term supply of raw material, respectively energy.
Recommendations: There is a need to develop a more robust and interdisciplinary methodological framework (adopted from Velis and Brunner, 2013; Hagelüken, 2014).The results of Chapter 6 showed that there are several hotspots for improvements among the different components, and with this, a more robust framework. Two potential suggestions for improvements are identified: (i) regarding MDA, the results of the component 'geological knowledge' considering the sub-component **quantity** showed potential for improvement in all operational steps. This could be overcome by similar investigations as in MDG. For instance, the mobility and concentration of resources are central to better understanding their quantity (Goodenough, Wall and Merriman, 2017). Congruently, it is suggested for MDA to understand for instance the EoL product formation, mobility and concentration as applied in Chapter 4. (ii) Regarding MDG and MDA, the 'economy', 'society' and 'environment' resulted in a similar potential for improvement for all investigated developing countries. This can be exemplified by the less stringent regulations toward social and environmental responsibility as observed in the utilisation of cheaper labour (Habib, Hamelin and Wenzel, 2016). For overcoming this imbalance, an EU initiative supports the achievement of the sustainable development goals of developing countries by three thematic groups: (i) an 'Africa Flagship Initiative' that supports growth in Africa, (ii) a 'Collect More Initiative' that fosters revenue mobilization, and (iii) a 'Spend Better Initiative' that strives to achieve tangible expenditure outcomes (Mboto Fouda, 2016). It is, therefore, recommended that hotspots from 'lower' accessibility countries are investigated in more detail to develop a more robust framework that is based on specific indicators. This in turn, could provide a basis for measuring the progress toward a green economy (BAFU, 2016).

6) **Consistent and interdisciplinary framework for evaluating raw materials supply.**

   Conclusions: Based on case study results regarding the same set of interdisciplinary indicators between MDA and MDG, it was found that the consistent framework facilitates the perception of MDA as a potential source of raw materials that is comparable with MDG, as requested by Winterstetter (2016). Additionally, as the results of the interdisciplinary framework showed, there are significant differences between developing and developed countries. In particular, the results of 'economy' demonstrated as 'higher' accessibility for developing countries and 'lower' accessibility for developed countries, whereas the results of 'society' and 'environment' demonstrated as 'lower' accessibility for developing countries and as 'higher' accessibility for developed countries. This indicates that there is a bi-polar situation.

   Recommendations: In Chapter 5 and Chapter 6, a consistent and interdisciplinary framework was developed. Whilst (i) the application of the same set of indicators has shown to be a comprehensive tool for raw material from both MDA and MDG at an early project development, and (ii) the results of the interdisciplinary indicators demonstrated a significant difference between developing and developed countries. This highlights the importance of investigating (i) both MDA and MDG in a consistent framework, which describes the accessibility by means of 'geological knowledge', 'eligibility', 'technology', 'economy', 'society' and 'environment', and (ii) combining the developing and developed countries in one perspective. In particular the results in the evaluation of 'economy' showed a factor 2 lower for developing countries than developed countries. The results in the evaluation of 'society' showed impacts with a factor 2.1 lower for developing countries than developed countries. This can have considerable influences on the accessibility of raw materials in the long-term. It is therefore advised that a consistent and interdisciplinary framework is considered for other raw material sources from both MDA and MDG in all countries worldwide to ensure a long-term security of material, respectively energy (BAFU, 2016; UK Research Council, 2016), as well as support the use of indicators for analysing the development toward a green economy (BAFU, 2016).

7) **Rethinking of raw material management.**

   Conclusions: There is an apparent lack of investigations regarding raw material accessibility, since current approaches only consider the availability of raw materials. In particular, the attempt to develop an understanding of accessibility that explicitly accounts for raw material depletion (USDOE, 1996) has failed, as current perspectives do not explicitly address 'how to get to the material'. Consequently, the currently used understanding of the term 'availability' lacks explicit considerations of 'approachability', which includes the 'attribute of being easy to deal or meet with' Chapter 5. While this thesis takes an important step in overcoming this deficiency by demonstrating the utility of the framework in eight case studies, there is need for further case study applications to demonstrate the wider utility of the accessibility evaluation.

Recommendations: There is a need to rethink raw material management (Ongondo *et al.,* 2015). In this thesis, this has been addressed by investigating raw material accessibility. Additionally, this research showed the potential benefits of a long-term supply of raw materials by explicitly addressing the approachability during early project development under sustainability considerations. To ensure the long-term accessibility of raw materials, it is recommended to apply an accessibility evaluation to different case studies. For this, it is suggested to investigate two different perspectives: (i) investing the different sourcing material such as EoL or Earth's crust deposits and (ii) investigating the different types of output material, such as Nd_2O_3. These applications in turn provide a basis for meeting research targets of securing the supply of material, respectively energy (BAFU, 2016; UK Research Council, 2016). These applications are further elucidated in the future research section 7.3.

7.3 Future research

The outcome of this thesis provides the basis for future investigations into diverse research topics, some of which are discussed below.

7.3.1 Advancement of the 'geological setting' characterisation

To contribute to the rapidly growing number of databases on quantifying information regarding resources in the anthroposphere, as developed in the ProSUM (Huisman *et al.*, 2017), there is a need for providing an overview perspective, as developed in the 'geological setting' characterization. Such an overview perspective should be systematic and narrowing (from broad to specific). This would be of considerable benefit to the development of any anthropogenic raw material inventory.

Additionally, with the current integration of sustainability in the UNFC classification (UNFC, 2017a, b, d) and the importance of considering the sustainable development goals (Lu *et al.*, 2015), there is a need to integrate additional criteria into the 'geological setting' characterization, which takes into account the broad sustainability considerations as applied in Chapter 5 and Chapter 6. These considerations would need to include: 'eligibility', 'technology', 'economy', 'society' and 'environment'. Such research would serve as a means of developing a systematic, narrowing and broad characterization of deposits for both MDA and MDG. This in turn facilitate the comparability of deposits from MDA and MDG as requested by Winterstetter (2016).

7.3.2 Advancement of the methodological framework

The eight applied case studies were selected according to appropriateness, representativeness, and the quality of available data. The case study selection was reliant on a few options that had enough detailed secondary data available. Among these secondary data, the quality was often limited and in some cases data were absent. This was particularly relevant for the research presented in Chapter 6. In this Chapter, the data quality was a source of uncertainty in the accessibility evaluation and reduced the overall reliability of the framework. To address the limited number of available case studies, it is recommended to apply the framework further. Additionally, this provides a chance for further advances of the accessibility framework regarding influences of by-products from sourcing deposits, or quantifying different output raw materials. For case studies regarding sourcing deposits, the MatCH project on quantifying the Swiss material consumption presents an important and detailed source of information (Gauch *et al.*, 2017). For case studies regarding output raw materials, the recently developed knowledge base from the projects such as ProSUM also provides a rich source of information, which quantifies the data uncertainty similarly as in this PhD research (Huisman *et al.*, 2017).

7.3.3 Data uncertainty

The methodological framework developed as part of this thesis, which evaluates the accessibility of raw materials from EoL products and the Earth's crust under sustainability considerations, includes a qualitative data ranking to investigate the uncertainty. The successful use of this framework provides an informative and qualitative investigation of the uncertainty. Additional research could refine the uncertainty investigation and provide a more reliable overall outcome for government. It should be considered to develop a combined uncertainty investigation that includes both (i) the current use of the data quality ranking and (ii) the Monte Carlo simulation for not directly 'inferred' indicators as applied by Graedel *et al.* (2012). Additionally, further methodological framework advancement could include a 'scenario' approach, as suggested in the specification to classify anthropogenic sources. This 'scenario' approach includes three discrete scenarios that reflect the range of uncertainty of the possible results (Heuss-Aßbichler *et al.*, 2017).

7.3.4 Further alignment with UNFC classification framework

The results of Chapter 5 demonstrate how the sub-classes and indicators were developed in line with the UNFC classification. In Chapter 6, this aggregation was not pursued further, since every aggregation that includes a weighting remains subjective and adds limited additional value to the interpretation of the results (Bach *et al.*, 2017). It is, however, recognised that an aggregated result can summarise complex and multi-dimensional realities, makes it easier to interpret the results, and facilitates communication with the general public and decision makers (Saltelli *et al.*, 2005). Consequently, further research is required to extend the current transparent representation of the indicator results with a systematic meta-level result description, similarly as suggested in the description of the developed sub-classes in Chapter 5. Thereby, it is central to preserve the current transparent representation of the various indicators. This would require a meta-level description with transparent representation of their individual results, yet providing a summary perspective. This could not only offer valuable insights to the overall accessibility evaluation but also would provide useful knowledge to the government and explicitly address the research targets of securing the supply of the material, respectively energy (BAFU, 2016; UK Research Council, 2016).

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Appendixes

Appendix A List of publications

In addition to the two publications Mueller *et al.* (2015) and Mueller *et al.* (2017), the following scientific contributions were produced during the period of PhD candidature. These contributions Mueller, S., *et al.,* (2014a) and Mueller, S. *et al.,* (2015) are attached in the appendix.

Mueller S. R. Geological exploration of urban mining linked with resource management approaches such as MFA, LCA (2014). *Presentation at Nanjing University, School of the Environment.* China.

Mueller, S., Wäger, P.A., Widmer, R. and Williams, I.D. (2014a) Characterising and evaluating waste electrical and electronic equipment as a source of scarce metals - a geological and primary production perspective. *Proceedings of SUM 2014 – Second Symposium on Urban Mining*. Italy, CISA Publisher, P091.

Mueller, S., Wäger, P.A., Shaw P.J., Ongondo F.O., and Williams, I.D. (2014b) Accessing critical raw materials from e-waste – a geological exploration perspective. *E-Waste Academy – Scientists Edition.* China.

Mueller, S., Wäger, P.A., Shaw P.J., Ongondo F.O., and Williams, I.D. (2015) Mining from Anthropogenic Deposits: Developing the Foundations to Evaluate the Accessibility of Rare Earth Metals From End of Life Products. *Proceedings of International Workshop on Technospheric Mining.* Austria.

Mueller, S. R., Wäger, P.A., Turner, D. A., Shaw P.J., Ongondo F.O., and Williams, I.D. Evaluating the Accessibility of Scarce Metals from End of Life Products and the Earth's Crust (2016) *Proceedings of Poster Presentation at Empa PhD Students Symposium 2016*. Switzerland. pp.78

Mueller S. R., Kral U., Fellner J. (2018) Resource Assessment of Municipal Solid Waste Streams: Testing the Applicability of the United Nations Framework Classification and its Specification for Anthropogenic Resources. *Report of Short Term Scientific Mission of Action number: CA COST Action CA15115*, from November 2017 to February 2018, at Technische Universität Wien, Austria. http://www.minea-network.eu/stsmgrantees.php (Accessed 12.03.2018) (on invitation)

Heuss-Aßbichler, S., Heiberg, S., Horváth, Z., Kral, U., Müller, F., Müller, S., Simoni, M., Wäger, P., Winterstetter, A., (2017) Draft specifications for the application of UNFC to anthropogenic resources. United Nations Economic Commission for Europe (UNECE), Geneva, Switzerland.

University of Southampton, The Students and Staff of the Centre for Environmental Science. (2017) ‘Millennials to the rescue?’, *Waste Management*, 62, pp. 1–2.

Peagram, R., Williams, I.D., Curran, T., Mueller, S.R., den Boer, E., Kopacek, B., Schadlbauer, S. and Musterle, J., (2014) Business-to-business end-of-life IT industrial networks. *Proceedings of the ICE - Waste and Resource Management*, 167(4), pp.178–192.

Appendix B Chapter 2

Table 25: Systematic review of 16 availability evaluation approaches. N/A stands for not available.

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
1	McKelvey Resource Classification and JORC (Weber, 2013)	Component	Yes in geological knowledge	YES in legal elements	Yes in processing	Yes in marketing and general cots and revenue elements or factors	Yes in social issues	Yes in environmental	Not assignable: - Climate, - supply logistics, Power sources - existing infrastructure - labour supply and skill level
		Indicator	Mining information, such as production rate scenarios, waste rock handling, Geotechnical / hydrological, such as slope stability, water balance and seismic risk	Legal elements or factors: security of tenure, ownership rights and interests, political risk, negotiated fiscal regime and environmental liability	Processing such as product recoveries, product recoveries, process selection	- Marketing elements or factors, such as product specification, transportation costs, - General cots and revenue elements or factors, such as commodity price forecasts and inflation	Social issues: Sustainable development strategy, impact assessment and mitigation, negotiated benefit agreement, cultural and social influences	Environmental, such as Baseline studies, tailings and waste rock management, acid rock drainage issues, and permitting schedule	
		Scoring	N/A	N/A	N/A	N/A	N/A	N/A	
		Aggregation	N/A	N/A	N/A	N/A	N/A	N/A	
2.1	UNFC-2009 (UNFC, 2010, 2016)	Component	Yes in geological knowledge	Yes in socio-economic viability	Yes in project feasibility	Yes in socio-economic viability	Yes in socio-economic viability	Implicitly in socio-economic viability	
		Indicator	Level of confidence in the	Socio-economic	Project feasibility:	Socio-economic	Socio-economic via-	Socio-economic	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
			geological knowledge and potential recoverability of the quantities.	viability: Non-technical issues: including legal/fiscal framework.	Maturity of implement mining plans or development projects.	viability: Non-technical issues: including commodity prices, operating costs.	bility: Non-technical issues: known social impediments or barriers.	viability: Non-technical issues: environmental regulations and known environmental impediments or barriers.	
		Scoring	N/A	N/A	N/A	N/A	N/A	N/A	
2.2	UNFC-2009 (focus on expansion with socio-environmental axis: eligibility, social and environmental reporting)	Component	Already reviewed, see earlier assessment	Already reviewed, see earlier assessment					
		Indicator		1) Legal framework (right to produce or sell) 2) Contractual conditions.		1) Fiscal framework	1) Active or non-active stake holder engagement 2) Regulatory approval (social approval, such as social license to operate)	1) Regulatory approval (environmental approval)	
		Scoring		1) - E1 if the legal right to produce and sell is established and not in dispute. - E2 if the legal right to produce and sell is being negotiated but not finalized, or is in dispute.		1) - E1 if established and not in dispute or uncertain in any manner. - E2 if it is being negotiated but not finalized, is in dispute, or there is uncertainty due to the possibility of a	1) E1 (active) to E3 (no attempt to become active) 2) - E1 if received or, in areas and jurisdictions where there is an established history of approval and approval is expected. - E2 if applied	1) - E1 if received or, in areas and jurisdictions where there is an established history of approval and approval is expected. - E2 if applied for but not yet received. - E3 if not	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
				- E3 if there is no legal right to produce and sell, as is the case for many exploration activities. 2) - E1 if established, not in dispute or uncertain in any manner, and is expected to be concluded with a high degree of certainty. - E1 if established, not in dispute or uncertain in any manner, and is expected to be concluded with a high degree of certainty.- E2 if they are being negotiated but not finalized, are in dispute, or there is uncertainty due to the possibility of a change that could affect the economic		change that could affect the economic viability of a project. - E3 if not determined.	for but not yet received. - E3 if not applied for.	applied for.	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
				viability of a project. - E1 if established, not in dispute or uncertain in any manner, and is expected to be concluded with a high degree of certainty.					
		Aggregation	No aggregation						
3	Multi-dimensional methodology supporting a safeguarding decision on the future access to mineral resources MRoPI$_r$ (Mateus *et al.*, 2017)	Purpose	Safeguarding the access to mineral resources. Applied in Portugal						
		Component	Level of geological knowledge. Denoted as a critical dimension	N/A	N/A	Economic dimension	Societal and acceptance dimension (SDA)	Environmental dimension	
		Indicator	Level of geological knowledge	N/A	N/A	Economic dimension	Social development and acceptance	Environmental dimension	
		Scoring	4 complementary criterion that are individually scored from acceptable	N/A	N/A	5 complementary criterion that are individually scored from acceptable	5 complementary criterion that are individually scored from acceptable (0.25) to ex-	7 complementary criterion that are individually scored from acceptable	

N o	Study with date and purpose	Compo-nent / indica-tor	Geological knowledge	Eligibility	Technolo-gy	Economy	Society	Environ-ment	Remark
			(0.25) to excellent (1.00): G1: availability and quality of geological information, such as multiscale geological maps G2: regional exploration information, such as geochemical data G3: existence of past exploitation information G4. Up-to-date information on tract (specific area) with such as continuous sampling: LGK = $[(0.2G_1)QDA_1] + [(0.3G_2)QDA_2] + [(0.2G_3)QDA_3] +[(0.3G_4)QDA_4]$ (QDA = Qualitative data assessment)			(0.25) to excellent (1.00): Economic dimension 1: intrinsic value of a tract (specific area) Economic dimension 2: exploitation lifetime within a tract Economic dimension 3: general evaluation of contribution by active mine operation Economic dimension 4: domestic market relevance of active operation Economic dimension 5: significance of active operation Economic dimension = $[(0.25Ec_1)QDA_1] + [(0.20Ec_2)QDA_2] + [(0.2Ec_3)QDA_3] +[(0.2Ec_4)QDA_4] +[(0.15Ec_5)QDA_5]$	cellent (1.00): SDA 1: public acceptance SDA 2: compatibility with other land uses SDA 3: impact on population settlement and growth SDA 4: impact in direct/indirect job creation SDA 5: wealth improvement associated with mining SDA = $[(0.20SDA_1)QDA_1] + [(0.15SDA_2)QDA_2] + [(0.15SDA_3)QDA_3] +[(0.25SDA_4)QDA_4] +[(0.25SDA_5)QDA_5]$	(0.25) to excellent (1.00): Environmental dimension 1: compatibility of mining with other environmental values Environmental dimension 2: past exploitation activities Environmental dimension 3: weighting environmental impacts of active mining Environmental dimension 4: impact of foreseen disturbance Environmental dimension 5: mitigation and rehabilitation measures Environmental dimension 6: type of land used Environmental dimension 7: responsibility to buffer the mining	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
								waste / residues produced. Environmental dimension = $[(0.20Ev_1)QDA_1]$ + $[(0.20Ev_2)QDA_2]$ + $[(0.10Ev_3)QDA_3]$ +$[(0.15Ev_4)QDA_4]$ +$[(0.10Ev_5)QDA_5]$ +$[(0.15Ev_6)QDA_6]$ +$[(0.10Ev_7)QDA_7]$	
		Aggregation	$MRoPI_r$ = 5.5LGK +1.5(Economic dimsnsion+Environmental dimension+SDA) (higher weighting in LGK, since it is considered as the prevailing dimension)						
4	Minerals, critical minerals and the U.S Economy (NRC, 2008)	Component	Yes in - importance in use (impact of supply restrictions) with chemicals and physical properties, - availability (supply risk) of mining deposits in the geosphere with geological	Implicit in availability (supply risk) of mining the geosphere and anthroposphere with politics	Yes in availability (supply risk) of mining the geosphere with technology	Yes in - importance in use (impact of supply restrictions) with mineral uses, impacts on the U.S. economy - availability (supply risk) of mining deposits in the geosphere and anthroposphere with economy for mining	No	No	
		Indicator	- World reserve/production ratio - World reserve	- US Import dependence (%, 2006)	- % US consumption in existing uses for which substitu-	- US consumption (million $, 2006)	No	No	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
			base/production ratio - World by-product production as % of total world primary production		tion is difficult or impossible - Importance of growth in emerging uses that could overwhelm existing global production capacity - US secondary production from old scrap as % of US apparent consumption				
		Scoring	- World reserve/production ratio: ratio - World reserve base/production ratio : ratio - World by-product production as % of total world primary production: data if available, otherwise: nil, small, primarily coproducts, most,	- US Import dependence (%, 2006)	- Substitution: % US consumption - Importance of growth in emerging uses: 1 = low im-importance to 4 = high importance - US secondary Production: data if available, otherwise: na, negligible, small, sig-	Costs in million $, 2006			

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
					nificant				
		Aggregation	- Impact of supply restriction (importance in use): proportion of total U.S. market for mineral X in application times Impact of supply restriction = Weighted Score - Supply risk (availability): using the highest single availability factor score as the final horizontal axis score.						
5	Material Security (Oakdene Hollins, 2008)	Component	Yes in scarcity	Implicit in monopoly supply Implicit in political instability	Implicit in lack of substitutability	Implicit in global consumption levels	No	YES with focus on global warming, total material requirement and vulnerability to the effects of climate change in key supplying regions	
		Indicator	Predictions from Kohmei Halada of Japan's National Institute for Material Science (Halada, Shimada and Ijima, 2008)	- The major supplying country - the percentage of world supply for which that country is responsible (data available from Wikipedia, 2016) Political instability: World Bank's Governance Indicator's website (World Bank, 2016b)	- Substitutability (No reference available)	- Global consumption level (Halada, Shimada and Ijima, 2008)	No	- Global Warming Potential (GWP) (Frischknecht *et al.*, 2004) - Total Material Requirement (TMR) (Halada, Shimada and Ijima, 2008) - Vulnerability to the effects of climate change in key supplying regions (WBGU, 2008)	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
		Scoring	1 (Low) = not predicted to reach reserves by 2050 2 (Medium) = predicted to overrun reserves by 2050 3 (High) = predicted to overrun reserve base by 2050	1 (Low) = Concentration less than 33.3% in any country 2 (Medium) = Concentration between 33.3% - 66.6% in any one country 3 (High) = Concentration greater than 66.6% in any one country Political instability: 1 (Low) = Political Stability Percentile greater than 66.6% 2 (Medium) = Political Stability Percentile between.3% - 66.6% 3 (High) = Political Stability Percentile less than 33.3%	1 = high substitutability, 2 given when no data was available, 3 = low substitutability	1 (Low) = less than 1,000 tonnes/a 2 (Medium) = between 1,000 and 1,000,000 tonnes/a 3 (High) = more than 1,000,000 tonnes/a		GWP: 1 (Low) = less than 1 kgCO2 (e) per kg material extracted 2 (Medium) = between 1 and 100 kgCO2 (e) per kg material extracted 3 High) = more than 100 kgCO2 (e) per kg material extracted TMR: 1 (Low) = less than 100 tonnes/tonne mineral 2 (Medium) = between 100 and 10,000 tonnes/tonne mineral 3 (High) = more than 10,000 tonnes/tonne mineral Vulnerability to effects in climate change: 1 (Low) = 2 (Medium) = no data available 3 (High)	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
		Aggregation	No aggregation, separate consideration of all 8 indicators.						
6.1	Critical raw materials for the EU (EC, 2014)	Component	No	Implicit in country concentration and governance	Implicit in substitutability and recycling rate	YES in applications and EU 'megasector' value	No	Environmental performance index	
		Indicator		- Country concentration: Herfindahl-Hirschman Index (HHI) (Weber and Heinrich, 2012) with production data from 2010 to 2012 based on Roskill and Raw Materials Group (licensed as the database Raw Materials Data) - Governance: World Governance Index (WGI) (World Bank, 2016b)	- Substitutability no information, yet report difficulty in both scoring and data availability - Recycling rate (UNEP, 2011)	- End uses of raw material with Eurostat 2010 and 2006. - Gross value added (GVA) of end use 'megasector' in the EU		Environmental performance index (EPI) (EPI, 2016), note the EIP does not in all cases reflect the reality of the mining country	
		Scoring		Combining 'eligibility' with EoL recycling rate and substitutability	- Substitutability, relative scoring between 0 to 1 with expert judgement (1 least substitutable).	Allocating the proportions of end-uses to the 'megasector' of the EU.		No information available	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
		Aggregation		Supply risk: Combining production data with WGI then risk-reducing filter I: recycling, followed by risk reducing filter II: substitutability.		Economic importance: The scoring proportions are multiplied with the GVA. Finally, this is scaled according to the total EU gross domestic product (GDP).		No information on aggregation	
6.2	Critical raw materials for the EU (EC, 2017)	Component	Implicit in economic importance and supply risk	Implicit in supply risk	Implicit in supply risk	Implicit in economic importance and supply risk	Implicit in supply risk	N/A	
		Indicator	- Share of raw material in an end-use application - global supply	- use of a substitution index - HHI - import reliance	- EoL recycling rate	- substitute cost performance - Trade parameter	- WGI	N/A	
		Scoring	Combining proportional share in economic importance	- own calculation of substitution index by means of substitute cost-performance (SCP)	- revised calculation: input of EoL material to EU / (input of material from the Earth's crust to EU + input of EoL material to EU)	- revised developed calculation, allocating in revised and much more detailed formula	- revised determination in supply risk.	N/A	
		Aggregation	Summing of economic importance and supply risk	Summing of supply risk	Summing of supply risk	Summing of economic importance and supply risk	Summing of supply risk	N/A	
7	Risk list	Compo-	Implicit by-product met-	Implicit in production	Implicit in substituta-	No	No	No	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
	2015 (BGS, 2015)	nent	al fraction and reserve distribution	concentration, governance of top-producing nation and top-reverse-hosting nation	bility and recycling rate				
		Indicator	- By-product metal fraction: data from (Graedel *et al.*, 2015) - Reserve distribution: mineral reserve data from the USGS	- Production concentration: The BGS' World Mineral Production data (2009 – 2013) - Governance: World Bank (WB) governance indicators with data from 2010 (World Bank, 2016b)	- Substitutability: (Achzet *et al.*, 2011) and (EC, 2010) - Recycling rate (recyclability) (UNEP, 2011)				
		Scoring	- By-product metal fraction: 1 (low) = <33.3 % 2 (medium) = >33.3 to 66.6 % 3 (high) = >66.6 % - Reserve distribution: 1 (low) = <33.3 % 2 (medium) = >33.3 to 66.6 %	- Production concentration: 1 (low) = <33.3 % 2 (medium) = >33.3 to 66.6 % 3 (high) = >66.6 % - Governance: 1 (high) = >66.6 % 2 (medium) = >33.3 to 66.6 % 3 (low) =	- Substitutability: 1 = Low (Achzet *et al.*, 2011) or <0.3 (EC, 2010) 2 (Achzet *et al.*, 2011) = Medium or 0.3 to 0.7 (EC, 2010) 3 (Achzet *et al.*, 2011) = High or >0.7 (EC, 2010)With out data, an arbitrary score				

No	**Study with date and purpose**	**Component / indicator**	**Geological knowledge**	**Eligibility**	**Technology**	**Economy**	**Society**	**Environment**	**Remark**
			3 (high) = >66.6 % Without data from USGS, an arbitrary score of 1.5 was allocated.	<33.3 %	of 1.5 was allocated. - Recycling rate: 1 (high) = >30 % 2 (medium) = >10 to 30 % 3 (low) = <10 % Without data, an arbitrary score of 1.5 was allocated.				
		Aggregation	- Equally weighted sum. - Convert the scoring from 1 to 21 in 1 to 10.						
8	Critical Metals towards a decarbonisation of the EU Energy Sector (Moss *et al.*, 2013)	Component	Yes in limitations to expanding supply capacity with reserve estimates and by-product dependencies	Implicit in geopolitical factors: - Cross-country concentration of supply - Political risk related to major supplying countries.	No	Yes in market factors: - Likelihood of rapid global demand growth	No	No	General information: lack of dynamic only been partly addressed to date (Buijs et al., 2012).
		Indicator	Reserve estimates (USGS, 2012) and supply forecast (BGS, 2016; USGS, 2016) and by-product dependencies (various sources, de-	- Cross-country concentration of supply (USGS, 2012) - Political risk (Found for Peace,		Analysis of demand structure and demand forecasts: no detailed information available			

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
			pending on the metal)	2016; World Bank, 2016b)					
		Scoring	High: There is a strong by-product dependency with little opportunity to increase extraction rates or low reserves. Medium: There is a by-product dependency or severe under-investment. Low: Sufficient reserves and mining as primary product.	- Cross-country concentration of supply: High: Most of supply is concentrated in one country Medium: Most of supply is concentrated in two or three countries Low: Supply is dispersed among a number of countries - Political risk: High: The major producing countries have a high score for political risk (>60) Medium: The main producing countries have mixed scores for political risks Low: The main pro-		High: Industry forecasts expect rapid demand growth from several applications (e.g. close to double-digit growth) Medium: Industry forecasts expect moderate and steady demand growth Low: Industry forecasts expect slow or stable demand from mature applications			

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
				ducing countries have low political risk scores (<40)					
		Aggregation	Added up into scoring low, low-medium, medium, medium-high, high						
9	Metal criticality determination, national level (Graedel *et al.*, 2012)	Component	Yes in geological	Implicit in geopolitical, regulatory, substitutability and susceptibility:	Implicit in substitutability Implicit in susceptibility	- Implicit in importance	YES in social	YES, environmental implications Implicit in substitutability	Not assigned: Vulnerability to supply restriction: importance
		Indicator	Geological, technological and economic - depletion time (reserve and reserve base) (e.g. USGS, 2012) - By-product metal fraction (no information available on calculation)	Geopolitical: - worldwide governance indicator (World Bank, 2016b) - global supply concentration with HHI (Weber and Heinrich, 2012) Regulatory: - policy potential index (Fraser Institute, 2016) - net import reliance ratio from substitute over metal in	Substitutability: - substitute performance - substitute availability (Graedel *et al.*, 2012) Susceptibility: - global innovation index (INSEAD, 2015)	Importance: - national economic importance Annual material consumption (e.g. USGS, 2012) as a percentage of the GDP (e.g. U.S. Bureau of Economic Analysis) - percentage of population utilizing (UNU, 2012; World Bank, 2016a)	Social: human development index (HDI) (Kovacevic, 2010)	Environmental implications: - ReCiPe end point method Sub-categories: Human Health Ecosystems Substitutability: - environmental impact ratio for substituatabiliy →Environmental risk = 50 x EI substitute /	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
				focus (e.g. USGS, 2012) Susceptibility: - global innovation index (INSEAD, 2015)				EI Metal of focus (Goedkoop *et al.*, 2013)	
		Scoring	Transformed to index 1 (low) to 100 (high).	Geopolitical: - worldwide governance indicator converting scoring in 1 (low) to 100 (high) - global supply concentration converting scoring in 1 (low) to 100 (high) Regulatory: - policy potential index: converting scoring in 1 (low) to 100 (high) Susceptibility: - global innovation index scoring in 1 (low) to 100 (high)	Substitute Performance: Score Range Default Score Evaluation Score range: 75 – 100 = Poor substitute (score of 1) Score range: 50 – 75 Adequate substitute (score of 2) Score range: 25 – 50 = Good substitute (score of 3) Score range: 0 – 25 = Exemplary substitute (score of 4) Global innovation index: Transformation from 1 (min) to 7 (max) 1 (low) to	Averaged to index 1 to 100.	Transformation to 1 (low) to 100 (high)	Transformation to 1 (low) to 100 (high)	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
					100 (high)				
		Aggregation	- Equally weighted sum. - Convert the scoring in 1 to 100.						
10	Sustainable resource strategies in corporation (Tuma *et al.*, 2014)	Component	Implicit in risk of supply reduction with reserves and resources and risk of increase in by-product metal fraction	Implicit in risk of concentration and political risk	Implicit in supply reduction with recycling rate and risk of increase in demand with substitutability and demand increase of future technology	No	YES in risk of child labour, control of corruption and freedom of speech	YES in human health and ecosystem quality	This evaluation includes within the economic dimension: - risk of concentration - political risk - risk of supply reduction - risk of increase in demand Our definition, does not encompass these under economy
		Indicator	- Risk of supply reduction with reserves and resources: Static range of or reserve and resources (USGS, 2014) - By-product metal fraction: (SNL Metals & Mining, 2015)	- Risk of concentration: country concentration (USGS, 2014) and company concentration (SNL Metals & Mining, 2015) - Political risk: political stability with world governance index (World Bank, 2016b); policy potential (Fraser Institute, 2016) and Regulation (Kovacevic,	- Recycling rate(Graedel *et al.*, 2011) - Substitutability: with expert opinion (Graedel *et al.*, 2013) - Demand increase of future technology (Angerer, 2009)				

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
				2010)					
		Scoring	Expert survey for weighting: - Risk of supply reduction with reserves and resources: Static range of or reserve 6.2% and resources 3.4% - By-product metal fraction: 6.1 %	Expert survey for weighting: - Risk of concentration: country concentration 28% and company concentration 15.1% - Political risk: political stability 8.8% - Policy potential 4.4% - Regulation 5.1%	Expert survey for weighting: - Recycling rate 6.1% - Substitutability: with expert opinion 13.5% - Demand increase of future technology 10.6%		Maximum principle	Endpoint values	
		Aggregation	General aggregation is not target-aimed.	General aggregation is not target-aimed.	General aggregation is not target-aimed.	General aggregation is not target-aimed.	General aggregation is not target-aimed.	General aggregation is not target-aimed.	
11	Cumulated raw material effort VDI 4599 (Neugebauer, 2013)	Component	No	Implicit in security of supply	No	Implicit in vulnerability	No	Yes in environmental implication	
		Indicator		N/A		N/A		N/A	
		Scoring		N/A				N/A	
		Aggregation		N/A		N/A		N/A	
12	Integrated sustainability assess-	Aggregation	N/A	N/A	N/A	N/A	N/A	N/A	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
	ment for production and supply of raw material and primary energy carriers (Dewulf *et al.*, 2015).								
		Component	N/A	N/A	Technical with decreasing physical availability, technical efforts, lack of alternatives	Economic with market stability / volatility, geopolitical issues	Social/societal with international regulations, labor conditions	Environmental with threats for natural habitats (at the withdrawal site of natural resources), impacts of emissions on ecosystem quality (along the life cycle)	
		Indicator	N/A	N/A	Renewability, ore grade indicator, cumulative exergy demand, substitutability, recycling rate	Price volatility index, HHI	OECD supply chian due diligence initiative (red flag), child labour risk, forced labour risk, excessive working hours risk, injuries and fatalities risks, disability-adjusted life years	Habitat service lost, species lost	
		Scoring	N/A	N/A					
		Aggregation	N/A	N/A					
13	SCARCE method: critical resource use of Germany (Bach *et al.*, 2017)	Purpose	Enhance criticality assessment with societal acceptance (includes compliance with social and environmental standards) on country level.						

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
		Component	a) Socio-economic availability b) Vulnerability	Socio-economic availability	a) Socio-economic availability b) Vulnerability	a) Socio-economic availability b) Vulnerability	a) Socio-economic availability b) compliance with social standard	a) Socio-economic availability b) compliance with environmental standard	
		Indicator	a) Concentration of reserves a) Occurrence of co-production b) Share of global production b) domestic required demand b) Dependency on imports	- Concentration of production - Concentration of company - availability of purchasing strategies	a) Mining capacity a) Feasibility of exploration projects b) Substitutability b) Utilization in future technologies	a) Price fluctuations a) Trade barriers a) Demand growth b) Economic importance	a) Political stability b) Small scale mining b) Geopolitical risk b) Human right abuse	a) Physical availability b) Sensitivity of local biodiversity b) Water scarcity b) Climate change	
		Scoring	0 (low) to 1 (high)	0 (low) to 1 (high)	0 (low) to 1 (high)	0 (low) to 1 (high)	0 (low) to 1 (high)	0 (low) to 1 (high)	
		Aggregation	Equal weighting of each components and then estimating one final score.						
14	RESCHECK, resource criticality evaluation of scarce metals for small and mediums size companies (Spörri *et al.*, 2017)	Component	Natural abundance	1) Country dependence	1) Co-Production 2) Substitutability 3) Corporate innovation ability	1) Demand 2) Historic price volatility 3) Importance of profitability 4) Substitutability	2) Social implications	Environmental implications (with total environmental impacts)	
		Indicator	Average concentration of element in Earth's crust	1) global production concentration	1) Co-product vs. Primary product 2) - General	- Economic significance of co-product 1) Development of global pro-	Political Potential Index 2) - conflict mineral (yes	- Ecosystems, Resource depletion, human health	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
					availability - Functional performance of substitute 3) - Metal saving measures - Metal saving potential	duction of new applications 2) Price ration of previous 5-year period 3) - Percent of revenue impacted - Ability to pass-through costs increase to customers - strategic importance for business 4) procurement costs of substitutes	or no) - corruption perception index		
		Scoring	Risk level of components RL1 (very low risk) to RL 5 (very high risk)						
		Aggregation	Aggregating of mean value, no weighting is yet implemented						
15	Resilience in Material Supply Chains (Sprecher *et al.*, 2015)	Component	Yes in material properties	Implicit in stockpiling, long-term supply risk and short-term supply disruption	Implicit in substitution	Yes in investment in mining deposits in the geosphere and anthroposphere	No	No	
		Indicator	N/A	- Stockpiling: value and time of material required to be kept in stocks;	- Material substitution - Technological substitution	Material price			

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
				- Long-term supply risk: depletion of existing mines, societal trends, technological developments, and protective measures. - short-term supply disruption: influence on material price and quantities					
		Scoring	N/A: Dynamic modelling	N/A: Dynamic modelling	N/A: Dynamic modelling	N/A: Dynamic modelling			
		Aggregation	N/A: Dynamic modelling	N/A: Dynamic modelling	N/A: Dynamic modelling	N/A: Dynamic modelling			
16	GRI guidance (focus on eligibility, social and environmental reporting) (GRI, 2016a, 2016b, 2016c)	Component	Uniform reporting system of 3 sustainability pillars: Economy, society, environment						
			301: Materials 2016		302: Energy 2016	201: Economic Performance 2016; GRI 202: Market Presence 2016; 203: Indirect Economic Impacts	205: Anti-corruption 2016 401: Employment 2016; 402: Labor/Management Relations; 403: Occupational Health	303: Water 2016; 304: Biodiversity 2016; 305: Emissions 2016; 306: Effluents and Waste 2016; 307: Environ-	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
						2016; 204: Procurement Practices 2016; ; 206: Anti-competitive Behaviour 2016	and Safety 2016; 404: Training and Education 2016; 405: Diversity and Equal Opportunity 2016 ; 406: Non-discrimination 2016; 407: Freedom of Association and Collective Bargaining 2016; 408: Child Labor 2016; 409: Forced or Compulsory Labor 2016;410: Security Practices 2016; 411: Rights of Indigenous Peoples 2016; 412: Human Rights Assessment 2016; 413: Local Communities 2016; 414: Supplier Social Assessment 2016; Public Policy 2016 ; 416: Customer Health and Safety; 417: Marketing and Labeling 2016; 418: Customer Privacy 2016; 419: Socioeconomic Compliance 2016	mental Compliance 2016; 308: Supplier Environmental Assessment 2016	
		Indicator	N/A	N/A	N/A	N/A	N/A	N/A	
		Scoring	N/A	N/A	N/A	N/A	N/A	N/A	

No	Study with date and purpose	Component / indicator	Geological knowledge	Eligibility	Technology	Economy	Society	Environment	Remark
		Aggregation	N/A	N/A	N/A	N/A	N/A	N/A	

Appendix C 'Ability' terminology synonyms and definitions

Table 26: 'Ability' terminology synonyms and definitions. Legend: S: synset (semantic) relations; ('explanation'): meaning of term; n: noun; a: adjective; v: verb (WordNet, 2014).

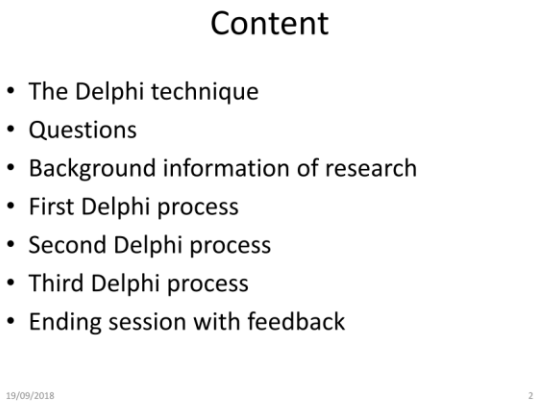
Term	WordNet cognitive synonym (synsets)
Ability	• S: (n) ability (the quality of being able to perform; a quality that permits or facilitates achievement or accomplishment) • S: (n) ability, power (possession of the qualities (especially mental qualities) required to do something or get something done) "danger heightened his powers of discrimination"
Accessibility	• S: (n) handiness, accessibility, availability, availableness (the quality of being at hand when needed) • S: (n) approachability, accessibility (the attribute of being easy to meet or deal with)
Approach ability	• S: (n) approachability, accessibility (the attribute of being easy to meet or deal with)
Availability	• S: (n) handiness, accessibility, availability, availableness (the quality of being at hand when needed)
Disposability	(note: noun not existent) → Adjective • S: (adj) disposable (free or available for use or disposition) "every disposable piece of equipment was sent to the fire"; "disposable assets" S: (adj) disposable (designed to be disposed of after use) "disposable paper cups"
Durability	• S: (n) lastingness, durability, enduringness, strength (permanence by virtue of the power to resist stress or force) "they advertised the durability of their products"
Extendibility	(note: noun not existent) → Adjective • S: (adj) extendible, extendable (capable of being lengthened)
maintainability	(note: noun not existent) → Adjective • S: (adj) maintainable (capable of being maintained)
Mineability	(note: noun not existent) → Verb • S: (v) mine (get from the earth by excavation) "mine ores and metals"
Recoverability	(note: noun not existent) → Adjective • S: (adj) recoverable (capable of being recovered or regained) "recoverable truth of a past event"
Recyclability	(note: noun not existent) → Adjective • S: (adj) reclaimable, recyclable, reusable (capable of being used again)
Reliability	• S: (n) dependability, dependableness, reliability, reliableness (the quality of being dependable or reliable)
Reusa-	(note: noun not existent) →

Term	WordNet cognitive synonym (synsets)
bility	Adjective • S: (adj) reclaimable, recyclable, reusable (capable of being used again)
Usability	• S: (n) serviceability, serviceableness, usableness, useableness, usability (the quality of being able to provide good service)
workability	(note: noun not existant) → Adjective • S: (adj) feasible, executable, practicable, viable, workable (capable of being done with means at hand and circumstances as they are)

Appendix D Chapter 3

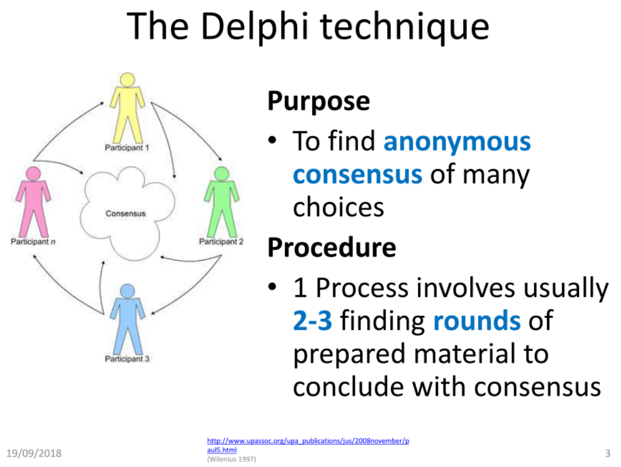
D.1 Presentation with questions for Delphi technique workshop

Characterising and evaluating waste electrical and electronic equipment as a source of scarce metals - applying a geological and primary production perspective



Content

- The Delphi technique
- Questions
- Background information of research
- First Delphi process
- Second Delphi process
- Third Delphi process
- Ending session with feedback



The Delphi technique

Purpose

- To find **anonymous consensus** of many choices

Procedure

- 1 Process involves usually **2-3** finding **rounds** of prepared material to conclude with consensus

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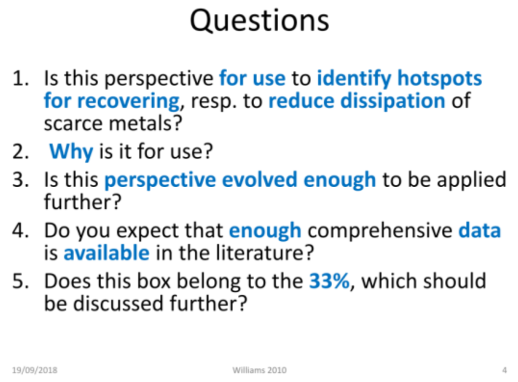

Questions

1. Is this perspective **for use** to **identify hotspots for recovering**, resp. to **reduce dissipation** of scarce metals?
2. **Why** is it for use?
3. Is this **perspective evolved enough** to be applied further?
4. Do you expect that **enough** comprehensive **data** is **available** in the literature?
5. Does this box belong to the **33%**, which should be discussed further?

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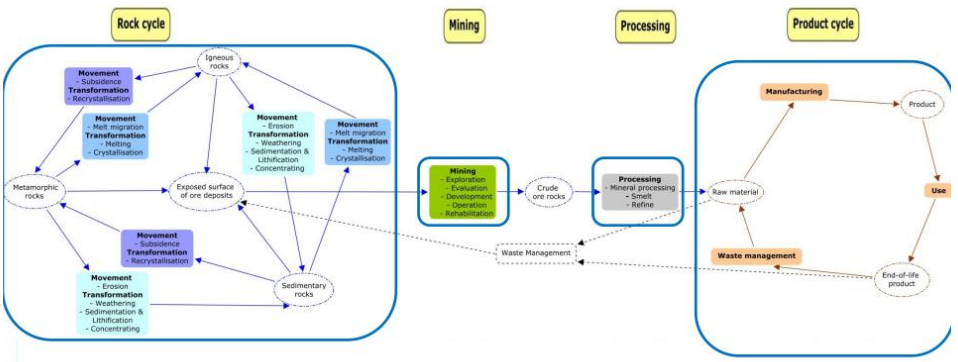
Background information of research



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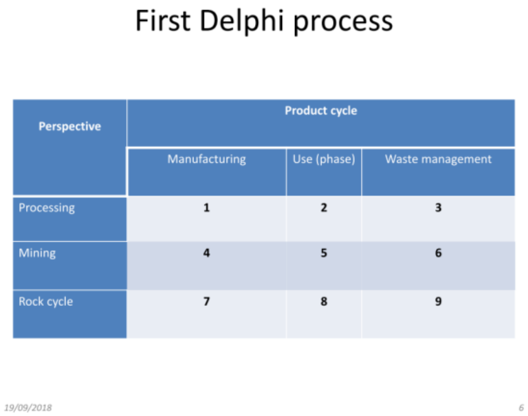

First Delphi process

Perspective	Product cycle		
	Manufacturing	Use (phase)	Waste management
Processing	1	2	3
Mining	4	5	6
Rock cycle	7	8	9

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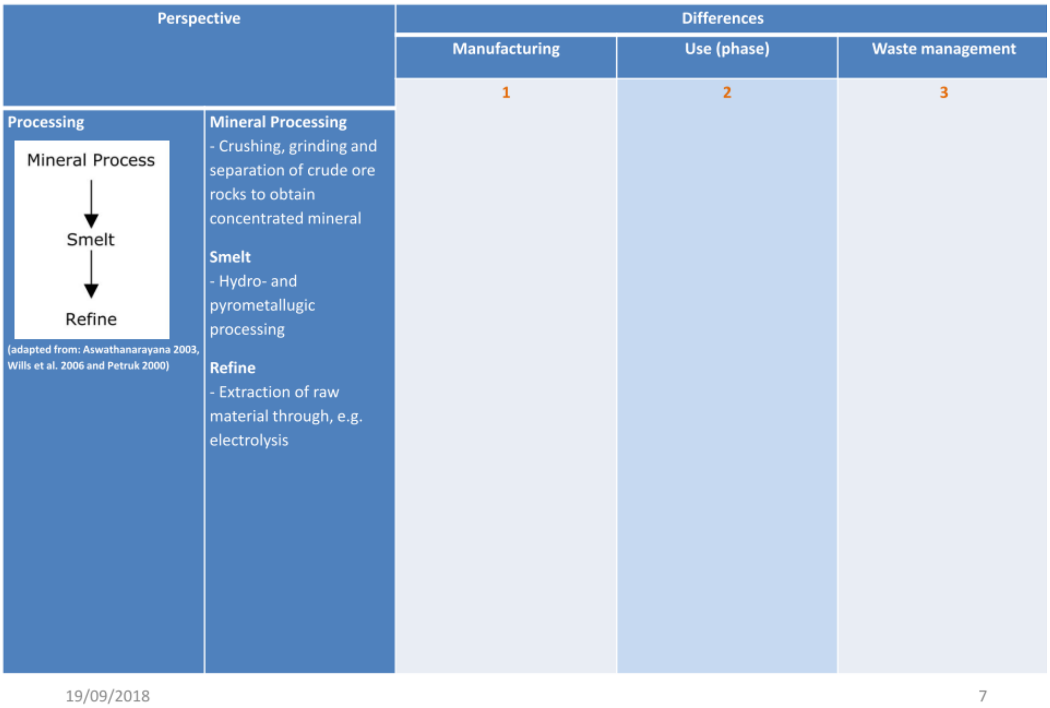
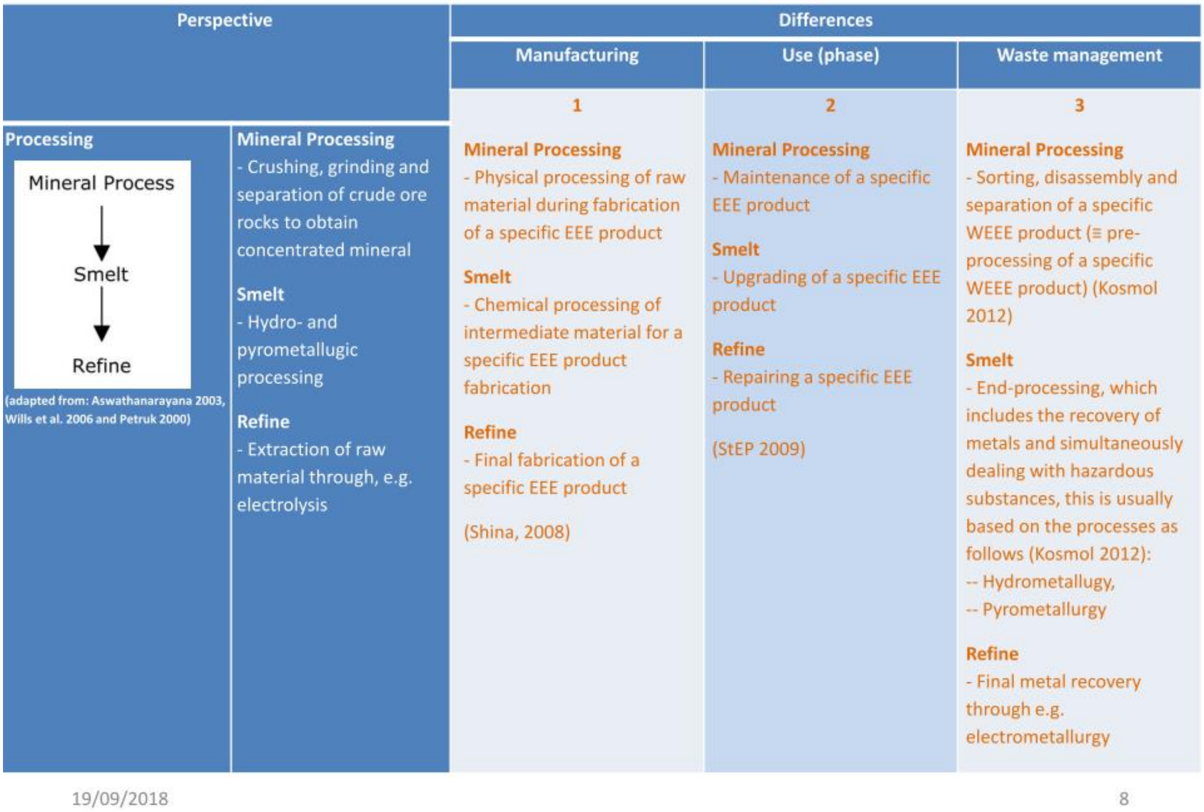


Perspective		Differences		
		Manufacturing	Use (phase)	Waste management
		1	2	3
Processing Mineral Process ↓ Smelt ↓ Refine (adapted from: Aswathanarayana 2003, Wills et al. 2006 and Petruk 2000)	**Mineral Processing** - Crushing, grinding and separation of crude ore rocks to obtain concentrated mineral **Smelt** - Hydro- and pyrometallugic processing **Refine** - Extraction of raw material through, e.g. electrolysis			



Perspective		Differences		
		Manufacturing	Use (phase)	Waste management
		1	2	3
Processing Mineral Process ↓ Smelt ↓ Refine (adapted from: Aswathanarayana 2003, Wills et al. 2006 and Petruk 2000)	**Mineral Processing** - Crushing, grinding and separation of crude ore rocks to obtain concentrated mineral **Smelt** - Hydro- and pyrometallugic processing **Refine** - Extraction of raw material through, e.g. electrolysis	**Mineral Processing** - Physical processing of raw material during fabrication of a specific EEE product **Smelt** - Chemical processing of intermediate material for a specific EEE product fabrication **Refine** - Final fabrication of a specific EEE product (Shina, 2008)	**Mineral Processing** - Maintenance of a specific EEE product **Smelt** - Upgrading of a specific EEE product **Refine** - Repairing a specific EEE product (StEP 2009)	**Mineral Processing** - Sorting, disassembly and separation of a specific WEEE product (≡ pre-processing of a specific WEEE product) (Kosmol 2012) **Smelt** - End-processing, which includes the recovery of metals and simultaneously dealing with hazardous substances, this is usually based on the processes as follows (Kosmol 2012): -- Hydrometallugy, -- Pyrometallurgy **Refine** - Final metal recovery through e.g. electrometallurgy

Mining		Manufacturing 4	Use (phase) 5	Waste management 6
Exploration and deposit discovery	**Exploration** - Genesis, characterisation of rock formation or sample drilling			
Evaluation	**Evaluation** - Study of the mining site according to the requirements in socio-economic viability, environmental, the project feasibility and the geological knowledge			
Development	**Development** - Development of mining approach			
Operation	**Operation** - Carrying out the ore mining within requirements			
Rehabilitation	**Rehabilitation** - Restoration of mine to its original condition			
(adapted from Mudd 2009)				

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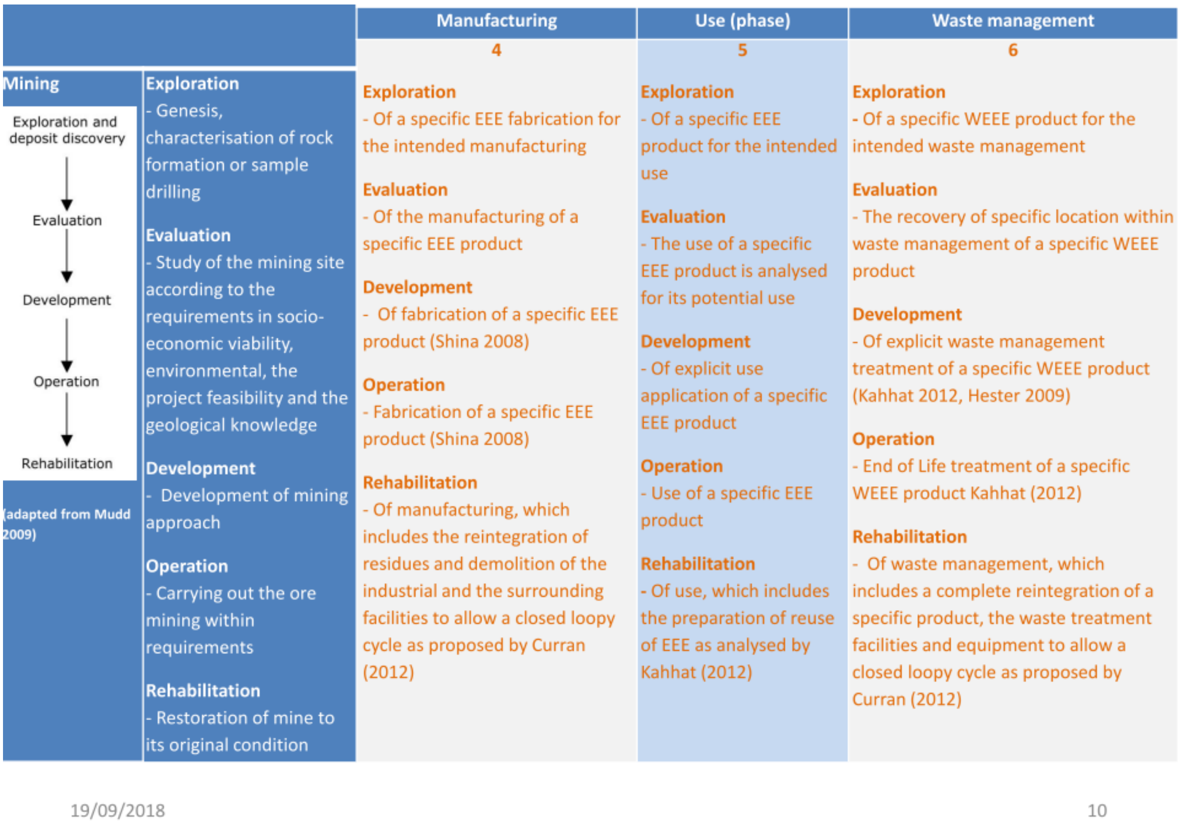

Mining		Manufacturing 4	Use (phase) 5	Waste management 6
Exploration and deposit discovery	**Exploration** - Genesis, characterisation of rock formation or sample drilling	**Exploration** - Of a specific EEE fabrication for the intended manufacturing	**Exploration** - Of a specific EEE product for the intended use	**Exploration** - Of a specific WEEE product for the intended waste management
Evaluation	**Evaluation** - Study of the mining site according to the requirements in socio-economic viability, environmental, the project feasibility and the geological knowledge	**Evaluation** - Of the manufacturing of a specific EEE product	**Evaluation** - The use of a specific EEE product is analysed for its potential use	**Evaluation** - The recovery of specific location within waste management of a specific WEEE product
Development	**Development** - Development of mining approach	**Development** - Of fabrication of a specific EEE product (Shina 2008)	**Development** - Of explicit use application of a specific EEE product	**Development** - Of explicit waste management treatment of a specific WEEE product (Kahhat 2012, Hester 2009)
Operation	**Operation** - Carrying out the ore mining within requirements	**Operation** - Fabrication of a specific EEE product (Shina 2008)	**Operation** - Use of a specific EEE product	**Operation** - End of Life treatment of a specific WEEE product Kahhat (2012)
Rehabilitation	**Rehabilitation** - Restoration of mine to its original condition	**Rehabilitation** - Of manufacturing, which includes the reintegration of residues and demolition of the industrial and the surrounding facilities to allow a closed loopy cycle as proposed by Curran (2012)	**Rehabilitation** - Of use, which includes the preparation of reuse of EEE as analysed by Kahhat (2012)	**Rehabilitation** - Of waste management, which includes a complete reintegration of a specific product, the waste treatment facilities and equipment to allow a closed loopy cycle as proposed by Curran (2012)
(adapted from Mudd 2009)				

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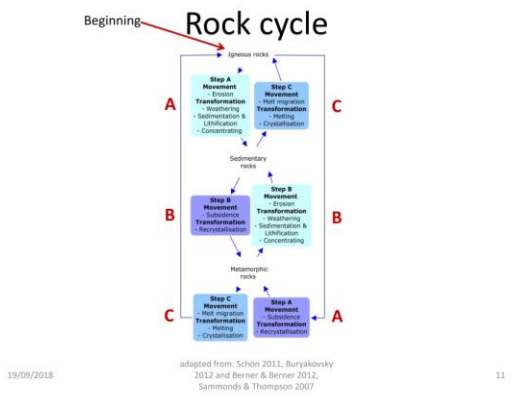
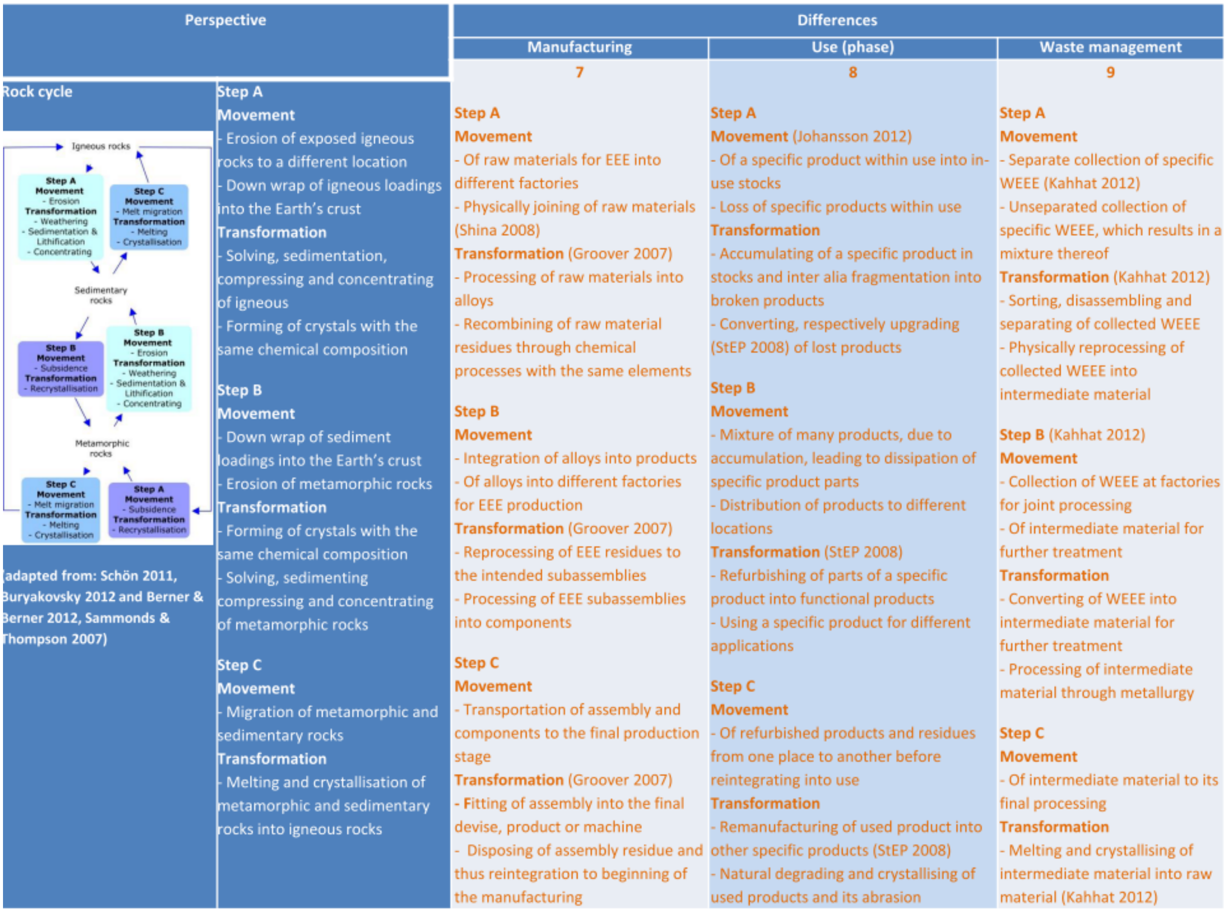

Rock cycle

adapted from: Schön 2011, Buryakovsky 2012 and Berner & Berner 2012, Sammonds & Thompson 2007



Perspective		Differences		
		Manufacturing	Use (phase)	Waste management
		7	8	9
Rock cycle **(adapted from: Schön 2011, Buryakovsky 2012 and Berner & Berner 2012, Sammonds & Thompson 2007)**	**Step A** **Movement** - Erosion of exposed igneous rocks to a different location - Down wrap of igneous loadings into the Earth's crust **Transformation** - Solving, sedimentation, compressing and concentrating of igneous - Forming of crystals with the same chemical composition **Step B** **Movement** - Down wrap of sediment loadings into the Earth's crust - Erosion of metamorphic rocks **Transformation** - Forming of crystals with the same chemical composition - Solving, sedimenting compressing and concentrating of metamorphic rocks **Step C** **Movement** - Migration of metamorphic and sedimentary rocks **Transformation** - Melting and crystallisation of metamorphic and sedimentary rocks into igneous rocks	**Step A** **Movement** - Of raw materials for EEE into different factories - Physically joining of raw materials (Shina 2008) **Transformation** (Groover 2007) - Processing of raw materials into alloys - Recombining of raw material residues through chemical processes with the same elements **Step B** **Movement** - Integration of alloys into products - Of alloys into different factories for EEE production **Transformation** (Groover 2007) - Reprocessing of EEE residues to the intended subassemblies - Processing of EEE subassemblies into components **Step C** **Movement** - Transportation of assembly and components to the final production stage **Transformation** (Groover 2007) - Fitting of assembly into the final devise, product or machine - Disposing of assembly residue and thus reintegration to beginning of the manufacturing	**Step A** **Movement** (Johansson 2012) - Of a specific product within use into in-use stocks - Loss of specific products within use **Transformation** - Accumulating of a specific product in stocks and inter alia fragmentation into broken products - Converting, respectively upgrading (StEP 2008) of lost products **Step B** **Movement** - Mixture of many products, due to accumulation, leading to dissipation of specific product parts - Distribution of products to different locations **Transformation** (StEP 2008) - Refurbishing of parts of a specific product into functional products - Using a specific product for different applications **Step C** **Movement** - Of refurbished products and residues from one place to another before reintegrating into use **Transformation** - Remanufacturing of used product into other specific products (StEP 2008) - Natural degrading and crystallising of used products and its abrasion	**Step A** **Movement** - Separate collection of specific WEEE (Kahhat 2012) - Unseparated collection of specific WEEE, which results in a mixture thereof **Transformation** (Kahhat 2012) - Sorting, disassembling and separating of collected WEEE - Physically reprocessing of collected WEEE into intermediate material **Step B** (Kahhat 2012) **Movement** - Collection of WEEE at factories for joint processing - Of intermediate material for further treatment **Transformation** - Converting of WEEE into intermediate material for further treatment - Processing of intermediate material through metallurgy **Step C** **Movement** - Of intermediate material to its final processing **Transformation** - Melting and crystallising of intermediate material into raw material (Kahhat 2012)

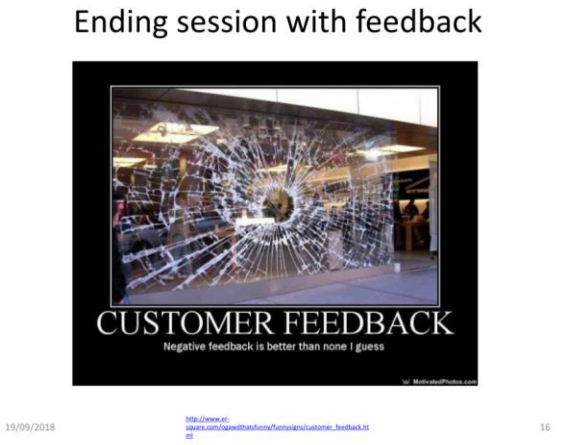
Second Delphi process

http://dannonay.blogspot.ch/2007/09/delphi-technique.html

Questions

1. Based on the workshop today, which **aspect** would be **worth exploring**?
    - Please write up to **1 aspects/cell** that might be worth researching

2. Please list the **two approaches** you consider the most promising (code no.)?



Ending session with feedback

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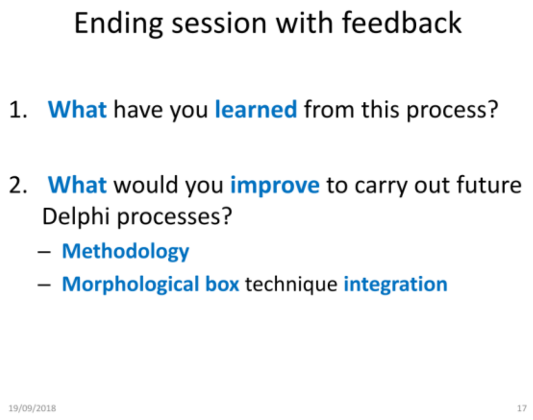

Ending session with feedback

1. **What** have you **learned** from this process?
2. **What** would you **improve** to carry out future Delphi processes?
   - **Methodology**
   - **Morphological box** technique **integration**

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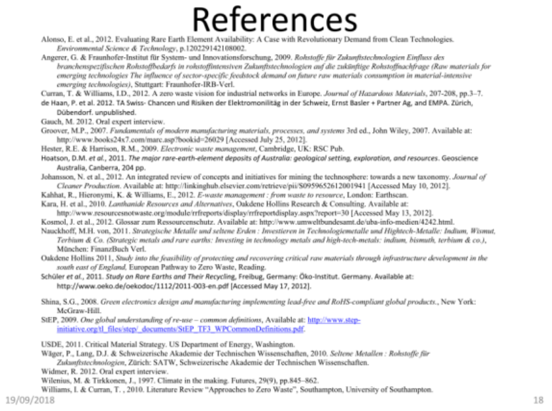

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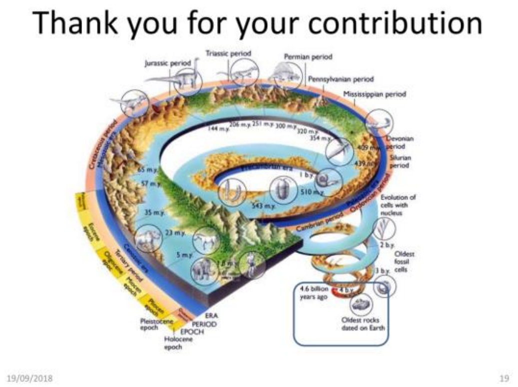

Thank you for your contribution

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D.2 Questionnaire for Delphi technique workshop

Evaluation Delphi rounds – participant

Round (please circle): 1 / 2 / 3 / 4 /

Cell number (please write the number based on your evaluation into the corresponding YES or NO cell): 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 /

Question		**Answer**					
		YES			**NO**		
A	Is this perspective for use to identify hotspots for recovering, resp. to reduce dissipation of scarce metals? (please insert the cell number from right to left)						
	Why is it for use?						

B	(please write 1 sentences only in the separate sheet)						
C	Is this approached evolved enough to be applied further? (please insert the cell number from right to left)						
D	Is it likely to be successful based upon previous application and use? (please insert the cell number from right to left)						
E	Are enough data, respectively comprehensive literature available? (please insert the cell number from right to left)						
F	Does this box belong to the 33%, which should be discussed further? (please insert the cell number from right to left)						

Evaluation Delphi rounds – participant

Round (please circle): 1 / 2 / 3 / 4 /

Answer sheet

Why is it for use?

(please write 1 sentences only)

Cell 1:……….

Cell 2:……….

Cell 3:...

Cell 4:...

Cell 5:...

Cell 6:...

Cell 7:...

Cell 8:...

Cell 9:...

Evaluation Delphi rounds – participant – generating ideas

Process (please circle): 3 /

Round (please circle): [✓ 1]/ 2 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Based on the workshop today, which aspect would be worth exploring to gain new insight (existing concepts)?

(Please write up to 1 aspect, with cell no., for each choice that might be worth researching)

- Cell :...

- Cell :...

3.

- Cell :…….

Evaluation Delphi rounds – participant – most promising ideas

Process (please circle): 3

Round (please circle): 1 / [✓ 2] /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Please list the two approaches you consider the most promising (code no.)?

No. ……………………

No. ……………………

Evaluation Delphi rounds – facilitator – large no. of choices

Process (please circle): 1 / 2 /

Round (please circle): 1 / 2 / 3 /

Cell number (please circle): 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 /

Question	**Evaluation** (please circle)		**Summary** **(If yes outweighs → please tick)**
Is this perspective for use to increase the recovering rate?	Yes No. participants:	No No. participants:	

Is this perspective evolved enough to be applied further?	Yes No. participants:	No No. participants:	
Do you expect that enough comprehensive data is available in the literature?	Yes No. participants:	No No. participants:	
Does this box belong to the 33%, which should be discussed further?	Yes No. participants:	No No. participants:	**Total share of participants propose further application, do only consider if 3/4 YES:**
Summary No. of Yes outweighs			**Total – no.:**
Further application, only if evaluation **Q outweigh Yes = 5** (please tick)			
Publish in power point	**- chosen cells with addition of:** **-- Summary why**		

Evaluation Delphi rounds – facilitator – generating ideas – summary

Process (please circle): 1 / 2 /

Round (please circle): 1 / 2 / 3 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

3th Delphi Processing

Q:

Based on the workshop today, which aspect would be worth exploring?

Please summarise the up to 12 aspects that might be worth researching?

1. ……….

2. ……….

3. ……

4. ……

5. ……

6. ……

7. ……

8. ……

9. ……

10. ……

11. ……

12. ……

Evaluation Delphi rounds – facilitator – most promising ideas

Process (please circle): 1 / 2 /

Round (please circle): 1 / 2 / 3 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Please summarise the 8 approaches you consider the most promising (code no.)?

1. No. ……………………

2. No. ……………………

3. No. ……………………

4. No. ……………………

5. No. ……………………

6. No. ……………………

7. No. ……………………

8. No. ……………………

➔ Majority of no.:

➔ Minority of no.:

➔ Average

4th ending session:

End: to collect oneself

Can you please give your feedback to this workshop regarding the methodology and outcome?

Note here the summary of the feedback:

Evaluation Delphi rounds – participant – generating ideas

Process (please circle): 3 /

Round (please circle): [✓ 1] / 2 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Based on the workshop today, which aspect would be worth exploring to gain new insight (existing concepts)?

(Please write up to 1 aspect, with cell no., for each choice that might be worth researching)

- Cell :……….

- Cell 8 :Phenomenological description of movement and transportation with e.g. economic / use. Et.c evaluation with accumulation

4.

- Cell :……….

Evaluation Delphi rounds – participant – most promising ideas

Process (please circle): 3

Round (please circle): 1 / [✓ 2] /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Please list the two approaches you consider the most promising (code no.)?

Appendix E Chapter 4

E.1 Transcripts of Delphi technique workshop

Evaluation Delphi rounds – participant 1

Round (please circle): 1 / 2 / 3 / 4 /

Cell number (please write the number based on your evaluation into the corresponding YES or NO cell): 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 /

Result round 1: numbers
Result round 2: green circle

Question		**Answer**					
		YES			**NO**		
A	Is this perspective for use to identify hotspots for recovering, resp. to reduce dissipation of scarce metals? (please insert the cell number from right to left)	3			1	3	
		4	5	6			
		7	8	5			
		-	-	-	-	-	-
B	Why is it for use? (please write 1 sentences only in the separate sheet)						
C	Is this approached evolved enough to be applied further? (please insert the cell number from right to left)	3			(1)	(2)	
					4	5	6
					7	8	9
		-	-	-	-	-	-
D	Is it likely to be successful based upon previous application and use? (please insert the cell number from right to left)			3	1	2	
		4	5	6			
					7	8	9
		-	-	-	-	-	-
E	Are enough data, respectively comprehensive literature available? (please insert the cell number from right to left)				1	2	3
					4	5	6
					7	8	9
		-	-	-	-	-	-
	Does this box belong			3	1	2	

F	to the 33%, which should be discussed further? (please insert the cell number from right to left)	4	(5)			(5)	6
		7	[✓ 8]				9
		-	-	-	-	-	-

Evaluation Delphi rounds – participant

Round (please circle): 1 / 2 / 3 / 4 /

Answer sheet

Why is it for use?

(please write 1 sentences only)

Cell 1:………

Cell 2:………

Cell 3:Because it is a similar compatible process

Cell 4:
Cell 5
Cell 6:

Because the relations of mines to finding sustainable deposits, then has to be applied onto the entire product life cycle. However on a different "levels": Manufacturing: a product; Use: all the products in use, incl. stocks; waste management, available end-of-life products

Cell 7:
Cell 8:
Cell 9:

Find a language to describe movement and transformation along the entire, whole product life cycle

Evaluation Delphi rounds – participant – generating ideas

Process (please circle): 3 /

Round (please circle): 1 / 2 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Based on the workshop today, which aspect would be worth exploring to gain new insight (existing concepts)?

(Please write up to 1 aspect, with cell no., for each choice that might be worth researching)

- Cell :…….

- Cell 8 :Phenomenological description of movement and transportation with e.g. economic / use. Et.c evaluation with accumulation

5.

- Cell :…….

Evaluation Delphi rounds – participant – most promising ideas

Process (please circle): 3

Round (please circle): 1 / [✓ 2] /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Please list the two approaches you consider the most promising (code no.)?

Evaluation Delphi rounds – participant 2

Round (please circle): 1 / 2 / 3 / 4 /

Cell number (please write the number based on your evaluation into the corresponding YES or NO cell): 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 /

Result round 1: numbers
Result round 2: green circle

Question		**Answer**					
		YES			**NO**		
A	Is this perspective for use to identify hotspots for recovering, resp. to reduce dissipation of scarce metals? (please insert the cell number from right to left)	3	2		1		
		6	4		5		
		8	9		7		
		-	-	-	-	-	-
B	Why is it for use? (please write 1 sentences only in the separate sheet)						
C	Is this approached evolved enough to be applied further? (please insert the cell number from right to left)	1			2	3	
		5			4	6	
					8	7	9
		-	-	-	-	-	-
D	Is it likely to be successful based upon previous application and use? (please insert the cell number from right to left)	2	3		1		
		4			5	6	
		8	9		7		
		-	-	-	-	-	-
E	Are enough data, respectively comprehensive literature available? (please insert the cell number from right to left)	1			2	3	
		5			4	6	
		7			8	9	
		-	-	-	-	-	-
F	Does this box belong to the 33%, which should be discussed further? (please insert the cell number from right to left)						
		3/5	8	9			
		-	[✓ +]	+/-			
		-	-	-	-	-	-

Evaluation Delphi rounds – participant

Round (please circle): 1 / 2 / 3 / 4 /

Answer sheet

Why is it for use?

(please write 1 sentences only)

Cell 1:……

Cell 2:……

Cell 3: ……

Cell 4: Too less knowledge about element / details in products

Cell 5: ……

Cell 6: ……

Cell 7: ……

Cell 8: ……

Cell 9: ……

Evaluation Delphi rounds – participant – generating ideas

Process (please circle): 3 /

Round (please circle): [✓ 1] / 2 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Based on the workshop today, which aspect would be worth exploring to gain new insight (existing concepts)?

(Please write up to 1 aspect, with cell no., for each choice that might be worth researching)

- Cell 8 : Todays use of Neodymium (Nd) dependents on Technology, which remove Nd for about 20 - 40 years out of the cycle
  → Substitution potential for Nd, independent of costs
  → Nowadays mining to be questioned, resp. small occurrence with high concentration versus high occurrence with small concentration

- Cell :…….

- Cell :…….

Evaluation Delphi rounds – participant – most promising ideas

Process (please circle): 3

Round (please circle): 1 / [✓ 2] /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Please list the two approaches you consider the most promising (code no.)?

Evaluation Delphi rounds – participant 3

Round (please circle): 1 / 2 / 3 / 4 /

Cell number (please write the number based on your evaluation into the corresponding YES or NO cell): 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 /

Result round 1: numbers
Result round 2: green circle

Question		**Answer**					
		YES			**NO**		
A	Is this perspective for use to identify hotspots for recovering, resp. to reduce	3			1	2	
		+/-4	6		5		
		8	9				

	dissipation of scarce metals? (please insert the cell number from right to left)	-	-	-	-	-	-
B	Why is it for use? (please write 1 sentences only in the separate sheet)						
C	Is this approached evolved enough to be applied further? (please insert the cell number from right to left)	3			1	2	
		4	6		3		
					8	7	9
		-	-	-	-	-	-
D	Is it likely to be successful based upon previous application and use? (please insert the cell number from right to left)	3			1	2	
		6	4		5		
		9		8	7		
		-	-	-	-	-	-
E	Are enough data, respectively comprehensive literature available? (please insert the cell number from right to left)	3			1	2	
		4	6		5		
					9	7	8
		-	-	-	-	-	-
F	Does this box belong to the 33%, which should be discussed further? (please insert the cell number from right to left)	[✓ 3]			1	2	
					4	5	6
		8	9		7		
		-	-	-	-	-	-

Evaluation Delphi rounds – participant

Round (please circle): 1 / 2 / 3 / 4 /

Answer sheet

Why is it for use?

(please write 1 sentences only)

Cell 1: Not useful, because manufacturing (assembly) 12 inverse of mineral disassembly for extracting element, resp. mineral processing.

Cell 2: Not useful, because use unlike mineral processing / extracting

Cell 3: Useful, because element extraction from waste has parallels to extraction from pre minerals

Cell 4: +/- Useful, because of exploration & knowledge discovering analogy to manufacturing optimisation (knowledge build up)

Cell 5: No, not enough knowledge about in-use stocks size & residence time

Cell 6: Useful, because of exploration

Cell 7: Could be further investigated but not interesting because already enough research done for manufacturing

Cell 8: Interesting because of mineral flow (distribution / concentration), analogies & deposit formation

Cell 9: see 8

Evaluation Delphi rounds – participant – generating ideas

Process (please circle): 3 /

Round (please circle): [✓ 1] / 2 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Based on the workshop today, which aspect would be worth exploring to gain new insight (existing concepts)?

(Please write up to 1 aspect, with cell no., for each choice that might be worth researching)

- Cell 8 : Step A: Weathering / Erosion (Transport / Movement) → Sedimantaion → Sediment → Large deposit, Small concentration → small deposit with high concentration. Or Deposit with small deposit, large concentration → 5mio car user with high deposits with small concentration.
  Step A: Seller of car to recycler with 5000 cars or Seller to carpark at home with only oldtimer with two cars

  spatial (& over time) transformation process describing with terminology from geology.

- Cell ……

- Cell ……

Evaluation Delphi rounds – participant – most promising ideas

Process (please circle): 3

Round (please circle): 1 / [✓ 2] /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 /
.13 / .14 / .15

Please list the two approaches you consider the most promising (code no.)?

Evaluation Delphi rounds – participant 4

Round (please circle): 1 / 2 / 3 / 4 /

Cell number (please write the number based on your evaluation into the corresponding YES or NO cell): 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 /

Result round 1: numbers
Result round 2: green circle

Question		**Answer**					
		YES			**NO**		
	Is this perspective for			3	1	2	

A	use to identify hotspots for recovering, resp. to reduce dissipation of scarce metals? (please insert the cell number from right to left)		5	6			
		7	8	9			
		-	-	-	-	-	-
B	Why is it for use? (please write 1 sentences only in the separate sheet)						
C	Is this approached evolved enough to be applied further? (please insert the cell number from right to left)			3	1	2	
				6	4	5	
				9	7	8	
		-	-	-	-	-	-
D	Is it likely to be successful based upon previous application and use? (please insert the cell number from right to left)		2	3	1		
				6	4	5	
				9	7	8	
		-	-	-	-	-	-
E	Are enough data, respectively comprehensive literature available? (please insert the cell number from right to left)			3	1	2	
					4	5	6
				9	7	8	
		-	-	-	-	-	-
F	Does this box belong to the 33%, which should be discussed further? (please insert the cell number from right to left)		(2)	3			
			(5)	6			
			8	9			
		-	-	-	-	-	-

Evaluation Delphi rounds – participant

Round (please circle): 1 / 2 / 3 / 4 /

Answer sheet

Why is it for use?

(please write 1 sentences only)

Cell 1:

Cell 2:

Cell 3:

Cell 4:

Cell 5:

Cell 6:

Cell 7:

Cell 8:

Cell 9:

Evaluation Delphi rounds – participant – generating ideas

Process (please circle): 3 /

Round (please circle): [✓ 1] / 2 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Based on the workshop today, which aspect would be worth exploring to gain new insight (existing concepts)?

(Please write up to 1 aspect, with cell no., for each choice that might be worth researching)

- Cell :

- Cell ……

- Cell ……

Evaluation Delphi rounds – participant – most promising ideas

Process (please circle): 3

Round (please circle): 1 / [✓ 2] /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Please list the two approaches you consider the most promising (code no.)?

Evaluation Delphi rounds – facilitator – large no. of choices

Process (please circle): 1 / 2 /

Round (please circle): 1 / 2 / 3 /

Cell number (please circle): 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 /

Question	**Evaluation** (please circle)		**Summary** **(If yes outweighs → please tick)**
Is this perspective for use to increase the recovering rate?	Yes No. participants:	No No. participants:	
Is this perspective evolved enough to be applied further?	Yes No. participants:	No No. participants:	
Do you expect that enough comprehensive data is available in the literature?	Yes No. participants:	No No. participants:	

Does this box belong to the 33%, which should be discussed further?	Yes No. participants:	No No. participants:	**Total share of participants propose further application, do only consider if 3/4 YES:**
Summary No. of Yes outweighs	**8, 9, 3**		**Total – no.:**
Further application, only if evaluation **Q outweigh Yes = 5** (please tick)			
Publish in power point	**- chosen cells with addition of:** **-- Summary why**		

Evaluation Delphi rounds – facilitator – generating ideas – summary

Process (please circle): 1 / 2 /

Round (please circle): 1 / 2 / 3 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

3th Delphi Processing

Q:

Based on the workshop today, which aspect would be worth exploring?

Please summarise the up to 12 aspects that might be worth researching?

13. ……

14. ……

15. ……

16. ……

17. ……

18. ……

19. …….

20. Check all areas → also manufacturing, use and waste management, use is considered as neutral, no one has done this yet, visualise use, not so fast duable, but a sketch could be drawn, e. g. material histories

21. Interesting WEEE and cycle has to be considered.

    into 3 levels: → what would be interesting, what doable and where is research need?

22. …….

23. …….

24. …….

Evaluation Delphi rounds – facilitator – most promising ideas

Process (please circle): 1 / 2 /

Round (please circle): 1 / 2 / 3 /

Cell number (please circle): .1 / .2 / .3 / .4 / .5 / .6 / .7 / .8 / .9 / .10 / .11 / .12 / .13 / .14 / .15

Please summarise the 8 approaches you consider the most promising (code no.)?

9. No. ……………………

10. No. ……………………

11. No. ……………………

12. No. ……………………

13. No. ……………………

14. No. ……………………

15. No. ……………………

16. No. ……………………

➔ Majority of no.:

➔ Minority of no.:

➔ Average

4th ending session:

End: “come together”

Can you please give your feedback to this workshop regarding the methodology and outcome?

Note here the summary of the feedback:

It was very difficult to fill in the answers, without being an expert in a particular area.

- ➔ Without TA it is almost impossible to make a conclusion.

Appendix F Chapter 5

F.1 Documents in copra: existing conceptualisations, mining the anthroposphere and mining the geosphere

F.1.1 Existing conceptualisations

Antonio M. Ávila-Muñoz, J.M.S.-S., 2014. Fuzzy sets and Prototype Theory: Representational model of cognitive community structures based on lexical availability trials. *Review of Cognitive Linguistics*, 12(1).

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Curl, A., Nelson, J.D. and Anable, J., 2011. Does Accessibility Planning address what matters? A review of current practice and practitioner perspectives. *Research in Transportation Business & Management*, 2, pp.3–11.

Envall, P., 2007. *Accessibility Planning: a chimera?* The University of Leeds, Institute for Transport Studies.

Fédération des Experts Comptables Européens, 2003. *Principles of Assurance: Fundamental Theoretical Issues with Respect to Assurance in Assurance Engagements*. Brussels, Belgium.

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Karlsson, C. and Gråsjö, U., 2013. *Accessibility: a useful analytical and empirical tool in spatial economics – experiences from Sweden*. [Working Paper Series in Economics and Institutions of Innovation] Royal Institute of Technology, CESIS - Centre of Excellence for Science and Innovation Studies. Available at: <https://ideas.repec.org/p/hhs/cesisp/0314.html> [Accessed 31 Aug. 2015].

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Klaesson, J., Larsson, J. and Norman, T., 2015. Accessibility and market potential analysis. In: *Handbook of Research Methods and Applications in Economic Geography*. Edward Elgar Publishing.

Makri, M.-C. and Folkesson, C., 1999. Accessibility measures for analyses of land use and travelling with geographical information systems. *Department of Technology and Society, Lund Institute of Technology, Lund University & Department of Spatial Planning, University of Karlskrona/Ronneby, Sweden*. Available at: <http://www.trafikdage.dk/td/papers/papers99/papers/paper/bpot/makri/makri.pdf> [Accessed 27 Aug. 2015].

Steen, J.A. and Mann, M., 2015. Human Rights and the Social Work Curriculum: Integrating Human Rights into Skill-Based Education Regarding Policy Practice Behaviors. *Journal of Policy Practice*, 14(3-4), pp.275–291.

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F.1.2 Mining the anthroposphere

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F.2 Method: text analysis

F.2.1 Statistical analysis

Coverage and distribution of the use of the words 'accessibility' and other related keywords were analysed. Word coverage aims to identify how often a term occurs and whether it is used in many different documents, whilst implying importance in meaning for a document. This is analysed following Zipf's law (Li, 1992), which can be used to identify the phenomena whereby in discourse a few words occur often, whilst the majority of words occur sparingly. For instance, the most frequent 150 words usually account for around half the words of a corpus (Powers, 1998). A frequent to sparingly word use is typically shown as a markedly difference in word coverage, such as 4 % to 0.2 %. This analysis was implemented, while the text body was scanned for the key terms ‘access*’ and ‘availab*’ (used to include all term derivations) using the NVivo (Castleberry, 2014) and PDF-XChange Viewer (PDF-XChange Viewer, 2014) software packages.

Distribution analysis aims to quantify terminological variance in sections of text and identify the distribution of the relative frequency of the most used terms. Here we created tag clouds to visually present the 100 most frequently used words in each corpus. Stop words, such as ‘about’, ‘some’ and ‘than’, were automatically excluded as implemented in NVivo (2016), since they generally have a low meaning for the understanding of text content (Weinhofer, 2010).

F.2.2 Semantic analysis

The meaning of conceptualisations, semantic field creation, collocation analysis and thematic classification were analysed. To identify a viable concept at the system level in the corpus EC literature, definitions of the word ‘accessibility’ were compared and contrasted. In parallel, a semantic field around ‘accessibility’ was established, which aims to provide the basis for connecting our conceptualisation of accessibility with the EoL products. For this, the material cycle was expressed with the accessibility root term ‘ability’. This further developed material cycle provided then the basis to link and transfer our accessibility definition and concept.

A collocation analysis was carried out on each of the three corpora. Collocation analysis is the most important and widely used investigation in corpus linguistics (Rychlý, 2008) and aims to statistically identify the proximity of semantically similar terms. This process is based on the assumption that terms close to each other are semantically important (Weinhofer, 2010). A simple example for a close collocation is ‘dog’ and ‘barking’. To prepare this analysis, first the ‘.pdf’ documents were transferred to ‘.txt’ files using the software package PDFlib TET (2016). Secondly, concordance[31] of the base form ‘accessibility’ and ‘availability’ in each corpus was established to create a morphological consensus of nouns, verbs, adjectives, or attributes with the terms of investigation (Granger and Paquot, 2012). To then analyse the collocation, the statistical association of possible term pairs were computed by means of logDice score (Equation 1). For this, we investigated the base forms ‘accessi-

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[31] ‘Concordance’ means agreement of a term with its textual environment, such as verb, adjective, or attribute to its origin noun form (Granger and Paquot, 2012).

bility' and 'availability' to terms used within the range: ±10 words[32] by using the platform Sketch Engine (Rychlý, 2008)

$$logDice = 14 + log_2 \frac{2fxy}{fx + fy} \quad \text{(Equation 1)}$$

Where fx is the number of occurrences of word *x*, fy is the number of occurrences of word *y* and fxy is the number of co-occurrences of words *x* and *y* in the range of ±10 words.

Subsequently, term pairs with the highest scores are presented as collocation candidates. For the corpus MG, no collocation could be established with 'accessibility'; consequently this term was adapted to 'accessi*'. The final score ranges from 0 to a theoretical maximum of 14 and the result is usually <10. A score of plus 1 means that a collocation occurs twice as often; and scores of plus 7 mean an approximately 100 times more frequent collocation (Rychlý, 2008). We assumed that 1 score below the usual maximum of 10, i.e. 9.00, implies that the term is highly important to describe 'accessibility' and its related terms.

F.3 Result: pre-processing

The following overlapping definitions and examples, taken from the literature, were considered:

- "*The quality of being at hand when needed*" with synonym 'availability' (Britannica Academic Dictionary, 2014; WordNet, 2014).
- "*Reached or easily got*" with synonym 'approachability' (Cambridge Dictionaries Online, 2014; Oxford Dictionary, 2014; WordNet, 2014)
- Common example in all dictionaries: "*access through infrastructure*" (Britannica Academic Dictionary, 2014; Cambridge Dictionaries Online, 2014; Oxford Dictionary, 2014)

Accessibility comprises the two synonyms 'availability' and 'approachability' 'Availability' denotes whether a raw material is close to hand but not necessarily retrievable and can be described by the sets of cognitive synonyms: 'handiness', 'accessibility', 'availability', availableness. 'Approachability' implies that a material is easily retrievable but not necessarily close at hand and can be described by the cognitive synonyms: 'approachability', 'availability'. 'Accessibility' thus expresses more in meaning than 'approachability' or 'availability' individually.

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[32] The average sentences length in academic writing is 20 – 30 words (Newell, 2014), consequently +/-10 words ensures an analysis of individual sentences.

F.4 Result: statistical text analysis

For the EC corpus, ‘accessibility’ was found to be used extensively in urban planning and economic geography, with usage ranging from 1.0% to 3.2%. Amongst the other subject areas – word usage was < 0.27%.

For the MA corpus, the word ‘accessibility’ was found to be used extensively in urban planning and economic geography in 138 of 141 documents with word coverage of < 0.40%. Amongst the other subject areas – word usage was < 0.27%.

For the MG corpus, the word ‘accessibility’ was used in 94 of the 116 documents. Eighty-eight of the 94 documents comprised ‘.The most frequently used terms are: mineral, production, resources, mining, ore, deposits, and data.

The statistical word coverage investigation of availability showed that this term is used within 94 of the 141 documents in the MA corpus.

F.5 Result: semantic analysis of accessibility conceptualisations by means of description, comparison and reflection of different ‘accessibility’ conceptualisations with illustrative examples and references.

Context	**Description of conceptualisations**	**Semantic analysis:** **Similarities and differences to the generic ‘accessibility’ definition**	**Examples and references**
Generic ‘accessibility’ definition	Approachability: “*the attribute of being easy to meet or deal with*” Availability: “*the quality of being at hand when neede*d” (WordNet, 2014)	-	-
Urban planning	Distance with impedance in a transport network, including ease to reach a location from origin A to destination B. Activity, respectively opportunity available at both locations A and B, which can involve places, people and activates (Envall,	**Similarity**: Clearly distinguishes between approachability by distance with impedance and availability by activities, respectively opportunities at a loca-	Urban Planning (Makri and Folkesson, 1999; Spiekermann et al., 2011; Weibull, 1980)

Context	Description of conceptualisations	Semantic analysis: Similarities and differences to the generic 'accessibility' definition	Examples and references
	2007). This can include restrictions through 'barriers' and 'constraints'.	tion. **Difference:** Focuses on establishing an optimal local urban system, rather than understanding 'accessibility' at a system level perspective.	
Economic geography	Ability to reach goods, services, activities or destinations. This accessibility measure represents the spatial distribution of economic attributes and their activities embedded in a specified and structured environment (Karlsson and Gråsjö, 2013).	**Similarity:** A rather generic understanding of accessibility that focuses on representing a system with a clear structure. **Difference:** Inclusion of spatial distribution with economic attributes that can reach goods, services, activities or destinations and not necessarily the 'quality' of being at hand.	Economic Geography (Karlsson and Gråsjö, 2013; Klaesson et al., 2015);
Geology	Provision of a raw material knowledge base that separately accounts for physical and technological attributes, i.e. bed thickness, depth and depletion of a country specific raw material base (USDOE, 1996).	**Similarities:** Includes approachability by technological attributes and availability by physical attribute. **Difference:** Focuses only on one aspect of the quality of being at hand when needed, i.e. availability.	US Department of Energy (USDOE, 1996)
Health science	Degree of reaching appropriate treatment of equal quality with	**Similarity:** Distinguishes and integrates	Health sciences (Jain, 1989; Lake

Context	Description of conceptualisations	Semantic analysis: Similarities and differences to the generic 'accessibility' definition	Examples and references
	ease, so treatment is available to anyone at any location (Lake et al., 2011).	both availability and approachability as per the generic definition. **Difference:** Here approachability strongly focuses on the aspect of quality.	et al., 2011; Steen and Mann, 2015; Wadman et al., 1981)
Linguistics	Degree of accessing literature with the principle, the more literature is available, the greater and quicker the accessibility is.	**Similarity:** Distinguishes and integrates both availability and approachability as per generic definition. **Difference:** The quality understanding of availability only includes the quantity of literature.	Cognitive linguistics (Antonio M. Ávila-Muñoz, 2014)
Information sciences	An existing mechanism by which the available information may be obtained, under the prerequisite if information is accessible, it must also be available.	**Similarity:** Distinguishes and integrates both availability and approachability. **Difference:** Not exactly specified if approachability also includes the attribute of being easy to meet.	Information policy (US Department of Commerce, 1981; Yurow, 1981; Fédération des Experts Comptables Européens, 2003)
Jurisprudence	Ability to reach the legislative information and documentation.	**Similarity:** Includes approachability as per the generic definition. **Difference:** Does not include availability.	(Keyes, 1993)

F.6 Result: semantic field development

The resulting semantic field development from relating the accessibility root term 'ability' with the cycle of a material is illustrated in Figure 26. From the outer layer, representing the 'Earth's crust', the 'crude ore at mining company' has a specific 'mineability' and 'processability' for producing 'metal at processor'. This in turn requires a particular 'manufacturability' to become a 'component', which is followed by a specific 'designability' to make products. Each product has a particular 'usability' with a potential 'extendability' until the product holder has no use for it and it becomes an 'end-of-life (EoL) product'. An 'EoL product' has either a specific 'disposability' into the 'Earth's crust'; or 'recyclability', 'reusability', 'remanufacturability'. The latter enables a circular material flow, rather than a linear one (Curran and Williams, 2012). Anthropogenic deposits occur at the 'EoL products' status and thus can only be accessed then. Moreover, the 'processability' process occurs twice within both the anthropogenic and geological material flows.

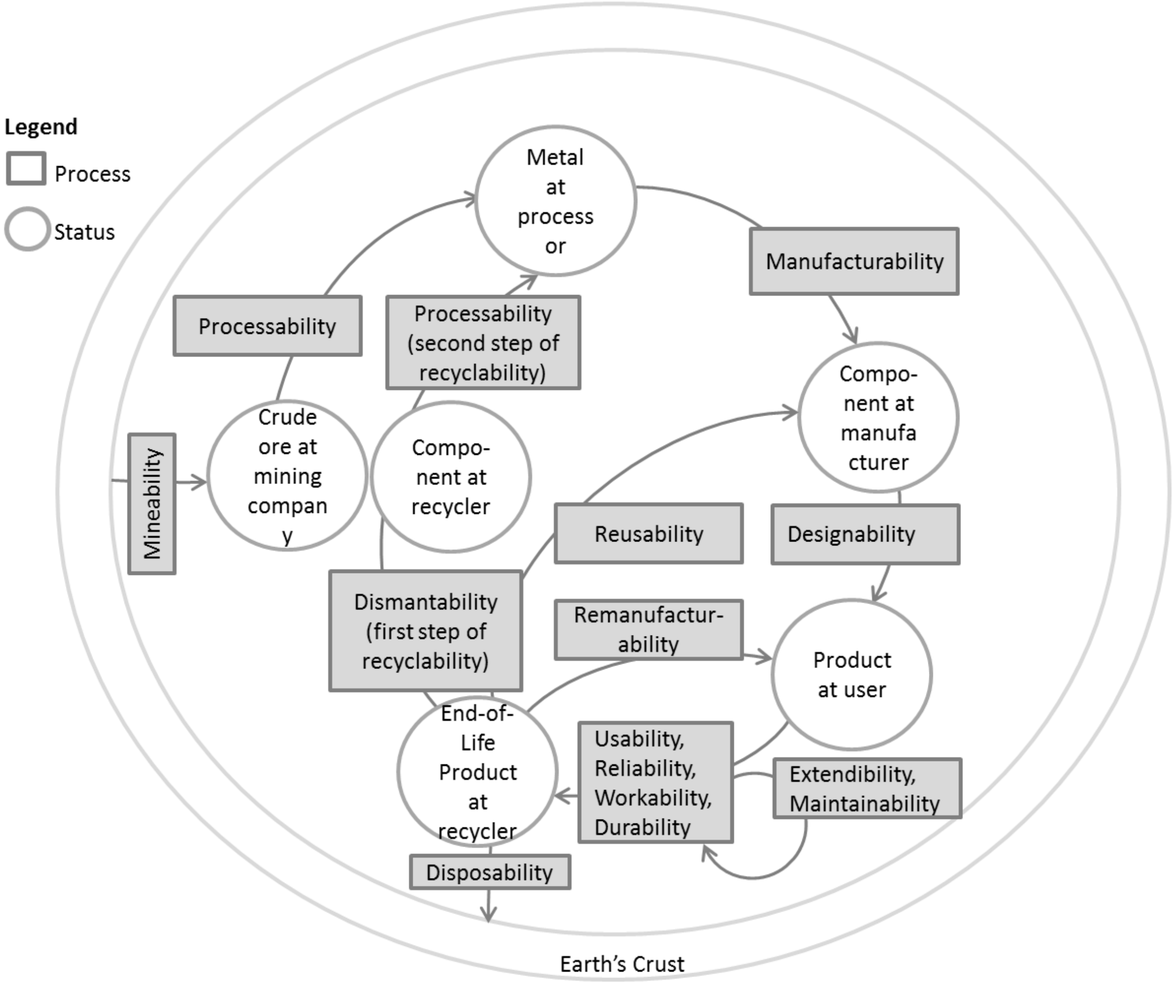


Figure 26: Semantic analysis: relationship of the cycle of a material and the established semantic field based on the accessibility root term 'ability' (Rankin, 2011; Reck and Graedel, 2012). The processes are in rectangular boxes and the ma-

terial statuses in round boxes.

F.7 Result: collocation analysis and thematic classification

Table 27: Collocation analysis from 'accessibility' with logDice algorithm and thematic classification. A logDice score >10, indicates a higher than usual collocation.

Term	logDice score	Component
Corpus: Existing conceptualisation		
Measure	12.34	Not applicable (n/a)
Indicator	11.76	n/a
Accessibility	11.71	n/a
Planning	11.43	n/a
Local	11.31	Geological knowledge
Use	11.23	Society, Eligibility
Transport	11.18	technology
Concept	10.47	n/a
Corpus: mining the anthroposphere (MA)		
Availability	7.76	n/a
Metallurgical	7.43	Technology
Location	7.36	Geological knowledge
Recycled	6.95	Technology
Scarcity	6.84	Eligibility
Component	6.72	n/a
Public	6.64	Society, Eligibility
Knowledge	6.62	Geological knowledge
Physical	6.58	Geological knowledge, Technology
Collection	6.42	Technology
Social	6.31	Society
Grade	5.90	Geological knowledge
Resource	5.51	Geological knowledge
Cost	5.30	Economy
Primary	5.25	Geological knowledge
Recycle	5.25	Technology
Market	5.24	Economy
Economic	5.22	Economy
Factor	5.21	Geological knowledge
Ore	5.15	Geological knowledge
Corpus: mining the geosphere (MG)		
Infrastructure	11.63	Technology

Table 28: Collocation analysis from 'availability' with logDice algorithm and thematic classification. A logDice score >10, indicates a higher than usual collocation.

Term	logDice score	Thematic classification

Table 28: Collocation analysis from 'availability' with logDice algorithm and thematic classification. A logDice score >10, indicates a higher than usual collocation.

Term	logDice score	Thematic classification
Corpus: mining the anthroposphere (MA)		
Resource	10.25	Geological knowledge
Data	9.62	n/a
Availability	9.60	n/a
Future	9.54	n/a
Supply	9.18	Eligibility
Physical	9.17	Geological knowledge, technology
Context	9.15	Geological knowledge
Scarcity	9.14	Eligibility
Reserve	9.05	Geological knowledge
Depletion	8.94	Eligibility
Geological	8.93	Geological knowledge
Mineral	8.89	Geological knowledge
Geologic	8.89	Geological knowledge
Quality	8.87	Geological knowledge
Economic	8.84	Economy
Long-term	8.76	Geological knowledge
Stock	8.73	Eligibility
Technology	8.40	Technology
Scrap	8.13	Geological knowledge
Social	8.01	Society
Metal	8.00	Geological knowledge
Corpus: Mining the geosphere (MG)		
Availability	10.70	n/a
Extrapolation	10.56	Geological knowledge
Distance	10.39	Geological knowledge
Physical	9.21	Geological knowledge
Future	9.19	Geological knowledge
Technology	9.10	Technology
Infrastructure	9.01	Technology
Concentration	8.99	Geological knowledge
Waste	8.88	Geological knowledge
Solid	8.77	Geological knowledge
Chemical	8.40	Geological knowledge
Cost	8.34	Economy
Quality	7.99	Geological knowledge
Property	7.74	Eligibility
Price	7.59	Economy
Mine	7.43	Eligibility
Environmental	7.40	Environment
Material	7.37	Geological knowledge

Table 28: Collocation analysis from 'availability' with logDice algorithm and thematic classification. A logDice score >10, indicates a higher than usual collocation.

Term	logDice score	Thematic classification
Resource	7.29	Geological knowledge
Mining	6.17	Technology
Mineral	5.60	Geological knowledge

F.8 Result: semantic analysis of availability

The collocation analysis of availability resulted in high collocations overall. For both MA and MG corpora, the collocations resulting in logDice scores >9.00 were assigned to the thematic classifications 'geological knowledge' and 'eligibility' only. This included the highest collocation candidates: 'resource', 'data', 'availability', 'future', 'supply', 'physical', 'context', 'scarcity', 'reserve', 'extrapolation', and 'distance'. For the first time the class 'environment' was assigned.

F.9 Result: detailed explanation on transferring the urban planning conceptualisation to this accessibility conceptualisation

The basic elements of this conceptualisation are summarised in Figure 27**a**. 'Original location' and 'opportunity available at destination' can be linked with 'availability', whist 'ease of interaction' can be linked with 'approachability'. For long-term raw material accessibility, sustainability is included in our conceptualisation and is also defined. The ensuing definitions are listed in Figure 27: Concept extraction: defining elements for our conceptual framework. (a) illustrating key elements of the 'accessibility' conceptualisation in urban planning; (b) illustrating the transferred urban planning conceptualisation to our 'accessibility' conceptualisation.Figure 27b. The definitions can be found in Table 29.

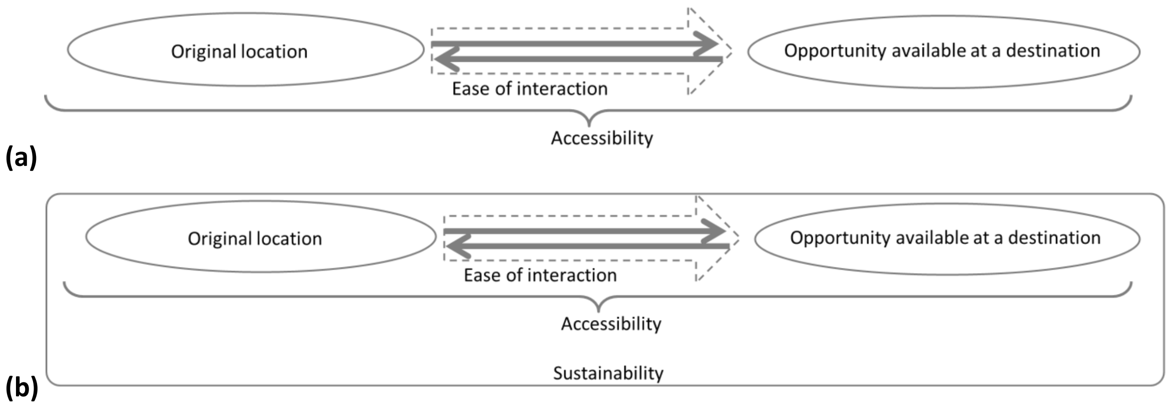


Figure 27: Concept extraction: defining elements for our conceptual framework. (a) illustrating key elements of the 'accessibility' conceptualisation in urban planning; (b) illustrating the transferred urban planning conceptualisation to our 'accessibility' conceptualisation.

Table 29: Definitions of the elements from the transferred urban planning conceptualisation.

Concept item	Definition
Original location	Availability: ‘Original location with opportunity’ in the geosphere and/or anthroposphere at relevant condition
Existing destination with opportunity	Availability: ‘Existing destination with opportunity’ in the geosphere and/or anthroposphere at ‘relevant’ condition.
Ease of interaction	Approachability: It is possible to ‘get to’ the material of interest with ease but it is unknown if the material actually exists at a ‘relevant’ condition
Accessibility	Raw materials are accessible if there are no ’significant’ constraints (e.g. ownership, protected areas, environmental restrictions) to ‘get to’ the material of interest in order for potential treatment or production.
Sustainability	“Certainly a sustainable society would use non-renewable gifts from the Earth’s crust more thoughtfully and efficiently than the present world does. It would price them properly, thereby keeping more of them [accessible to] future generations. But there is no reason not to use them, so long as their use meets the criteria of sustainability already defined, namely that they do not overwhelm a natural sink and that renewable substitutes are developed.” (adapted from Meadows, Randers and Meadows, 2004).

Appendix G Chapter 6

G.1 Framework refinement and confirmation, method: Delphi study invitation for round I

G.1.1 Expert initial invitation

Subject: Invitation to participate in a raw material supply survey

Dear *|FNAME|* *|LNAME|*

I am contacting you to invite you to participate in a survey on the current situation of the raw material supply.

The Centre for Environmental Science at the University of Southampton, in collaboration with the Swiss Federal Laboratories for Materials Science and Technology (Empa), are exploring how to quantitatively evaluate the accessibility of raw materials from End-of-Life products and the Earth's crust.

As you are recognised expert in the field of geology / industrial ecology / waste management, we would like to invite you to participate in this survey, which will take about 20 minutes of your time. This survey will be conducted entirely online and consists of two rounds. The second round will be conducted towards the middle of May 2017. Your confidentiality will be maintained as the data will remain anonymous in any publication of results. The second contact will be made by researcher NAME and E-MAIL

Please send a simple 'yes' if interested to E-MAIL by **Wednesday 19th of April**.

We would be happy to send you a summary report of the research results as a "thank you" in due course.

Kind regards,

G.1.2 Expert invitation with survey link

Subject: Participation in a raw material supply survey

Dear *|FNAME|* *|LNAME|*

Thank you for agreeing to participate in this survey.

This questionnaire will require about **20 minutes of your time.** Please complete your survey by the **9th May 2017**.

You can access the survey via: LINK

Thank you once more in advance for your contribution. As a thank you, a summary of our general findings will be shared with you.

Kind regards,

G.1.3 Friendly reminder with survey link

Subject: Friendly reminder to participate in a raw material supply survey

Dear *|FNAME|* *|LNAME|*

Thank you for agreeing to participate in this survey. If you have already completed this survey, please simply ignore this e-mail.

This is a friendly reminder of the approaching **deadline: this Tuesday, 9thMay 2017**. We understand you are very busy with work but we would very much value your expertise **during 20 minutes**.

You can access the survey via: LINK

As a thank you, a summary of our general findings will be shared with you.

Kind regards,

G.2 Framework refinement and confirmation, method: Delphi study invitation for round II

G.2.1 Expert invitation with survey link

Subject: Invitation to participate in second and final survey on the raw material supply

Dear *|FNAME|* *|LNAME|*

Thank you very much for your participation in the first round of our survey on the current situation of the raw material supply.

As a reminder, the Centre for Environmental Science at the University of Southampton, in collaboration with the Swiss Federal Laboratories for Materials Science and Technology (Empa), are exploring how to quantitatively evaluate the accessibility of raw materials from End-of-Life products and the Earth's crust.

We have collated the results from the first round and we are ready to proceed with the second round. We are very grateful that you have agreed to participate in the second round, especially as we realise how busy you must be.

This questionnaire will again require **about 20 minutes** of your time. **Please complete** your survey **by the 31st May 2017**.

Please note that in the second round we will present you with some of the results from the first round survey. The **purpose of the second round** is to ask you **to reflect on the experts' summarised views**. We are asking you to either confirm your initial view or amend it as upon reflection as a mechanism for securing higher quality and more resilient data. We are not questioning anyone's initial judgement, we are just asking you to reflect on the group's overall opinion as a mechanism for refining your own opinion.

You can access the survey via: LINK

As promised, **our general findings will be shared** with you.

We are extremely grateful for your time and support in helping us with our study.

Kind regards,

G.2.2 Friendly reminder with survey link

Subject: Gentle reminder for participation in second and final survey on the raw material supply

Dear *|FNAME|* *|LNAME|*

Thank you for agreeing to participate in this survey.

This is a friendly reminder of the approaching **deadline: next Wednesday, 31th May 2017**. We understand you are very busy with work but we would very much value your expertise **during 20 minutes**.

You can access the survey via: LINK

Thank you in advance for your contribution. As a thank you, a summary of our general findings will be shared with you.

Kind regards,

G.3 Framework refinement and confirmation, method: Delphi study questionnaire for round I

In this questionnaire, some of the sub-component and indicator terms were further developed (Table 30). This does not affect the underlying meaning of the terms.

Table 30: Clarification of terms further developed in this paper and as used in the questionnaire for Delphi study round one.

Term further developed	Term as used in the questionnaire
Market concentration	Ownership
Costs for collecting, mining and processing	Costs
Cost volatility for collecting, mining and processing	Cost volatility
Total environmental impacts	Environment and human health
WGI 'rule of law'	Rule of law
Indexed annual rate of collection, mining recovery and processing recovery	Annual rate of collection, mining recovery and processing recovery
Exergy replacement costs	Exergy
Political stability	Political stability and absence of violence/terrorism

Deposits: Evaluating the Accessibility of Scarce Metals from End-of-Life Products and the Earth's Crust

Introduction

An End-of-Life product mine

A geological mine

What is this research about?

This survey is part of a project in which we are exploring how to **quantitatively evaluate the accessibility of metals** from End-of-Life (EoL) products and the Earth's crust. This evaluation can be used to provide an early project stage indication about the development of an 'EoL product mine', which can be compared with a geological mine. Our survey is about **capturing the status of the current mining and processing** and not about your personal opinion. This inquiry consists of the following 3 sections and will require in total about **20 minutes of your time:**

A) Assessing the importance of sub-components (an overarching theme)
B) Assessing the importance of indicators (quantitatively indicating the condition of a status in particular)
C) Your background

Please read the following information carefully.

Please complete your survey by the **09th of May 2017**.

Why have I been chosen?

With your experience in working with evaluation on geology, waste management, industrial ecology, or sustainability assessment you will enhance the quantification of components and sub-components with indicators related to geological knowledge, eligibility, technology, economy, society and environment. This very much supports the understanding of the current raw material accessibility.

What will happen to me if I take part?

You are kindly invited to participate with your expert knowledge in two online survey rounds, with duration of about 20 min for each.

Are there any benefits in my taking part?

Your participation will kindly be rewarded with our general findings of the survey.

Are there any risks involved?

There are minor risks involved. The information that is provided during the survey will be stored on a password protected computer, and only be used for the purpose of this study. Only the results of ranking questions will be published in the PhD thesis and any journal articles arising from this study.

Will my participation be confidential?

Any information provided here will be compliant with the Data Protection Act and confidentiality policies of the University of Southampton. Data will be stored on a password protected computer and will not be disclosed to third parties.

What happens if I change my mind?

You have the right to withdraw at any time without affecting your legal rights.

What happens if something goes wrong?

In the unlikely case of concern or complaint, please refer all correspondence to the Research Governance Manager or the researcher in charge: NAME at the University of Southampton.

For Research Governance Manager please email: E-MAIL address.

For the researcher in charge NAME please email: E-MAIL address

Where can I get more information?

For more information, please contact the principal researcher NAME and E-MAIL address.

*Before commencing this survey, we need you to consent the following items.

1. I have read and understood the information above and have had the opportunity to ask questions about the study.

2. I agree to take part in this research project and agree for my data to be used for the purpose of this study.

3. I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected.

4. I am happy to be contacted regarding other unspecified research projects. I therefore consent to the University retaining my personal details on a database, kept separately from the research data detailed above. The ‘validity’ of my consent is conditional upon the University complying with the Data Protection Act and I understand that I can request my details be removed from this database at any time.

Data Protection

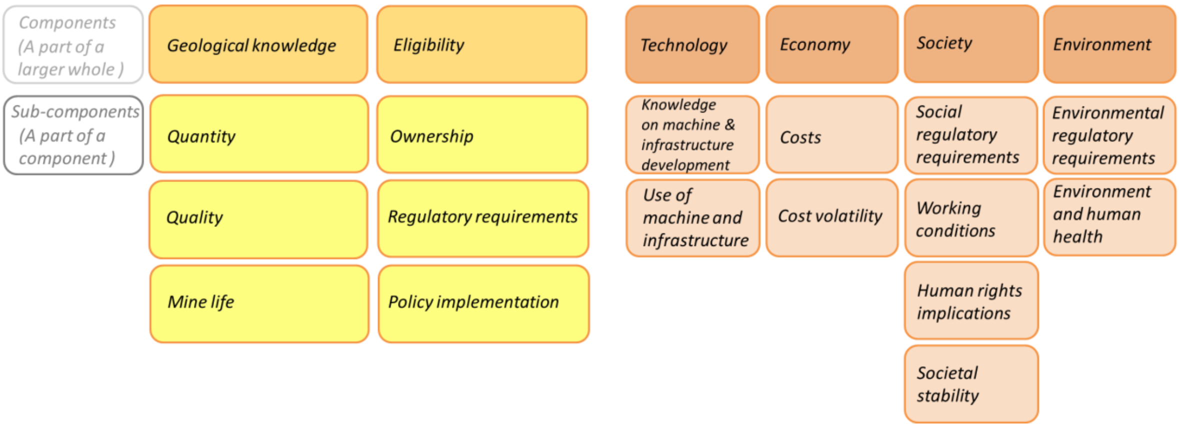
I understand that information collected about me during my participation in this study will be stored on a password protected computer and that this information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Thank you in advance for participating. As a thank you, our general findings will be shared with you. You will be offered to participate in a second survey round. For this you will be contacted again in mid-May 2017.

1. **If you consent the items 1-4, please click ‘yes’ and then ‘Next’ at the bottom of this page.**

Circle: yes (Online, tick shown)

A) Assessing the importance of sub-components



Please bear the following in mind, while answering these questions**:**

1. This survey considers the **current global mining and processing situation** independent from the sources: 'End-of-Life products' and the 'Earth's crust'
2. All of the questions are related to **accessibility of metals**.
3. Please respond based on **your experience**.
4. '**Accessibility**' means raw materials are accessible if there are no significant constraints (e.g. financial, technological and environmental restrictions) to 'get to' the material of interest in order for potential treatment or production.
5. '**Importance**' means the fact of being of great significance or value.

Please circle (online-version: click the circle) one value for each indicator and state your reason

2. * In general terms, how important are these sub-components for **geological knowledge**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Quantity The annual flow of a material from a deposit containing rock or End-of-Life products. This provides information about the annual mass flow of material collection/ mining and processing.	0	1	2	3	4
Quality	0	1	2	3	4

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
A characteristic of a rock or End-of-Life (EoL) product. This provides an indication on the mass fraction of ore in rock or component in EoL product.					
Mine life Expected duration of ore production from a mine (operational step: mining) and End-of-Life product generation (operational step: collection). This provides information on the duration of mining, collection and processing from a deposit.	0	1	2	3	4
Would you use any additional sub-components to describe geological knowledge? (please state)					

3. * In general terms, how important are these sub-components for **eligibility?**
'**Eligibility**' means having the right to do or obtain something and satisfying the appropriate conditions

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Ownership The state or right of possessing something. This provides an orientation about the clarity of ownership during collection/ mining and processing.	0	1	2	3	4
Regulatory requirement A rule or directive made and maintained by an authority. This	0	1	2	3	4

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
provides an orientation on the quality of contract enforcement and property rights.					
Policy implementation Principle of action adopted by an organization. This provides an orientation on the attractiveness of implementing mining projects.	0	1	2	3	4
Would you use any additional sub-components to describe eligibility? (please state)					

Note: in the online version a respond to one answer per question, which cannot be the same to the second and third question, was activated to ensure there is a differentiation between the three questions

4. * In general terms, how important are these sub-components for **technology**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Knowledge of machine and infrastructure development The information and skills about machines and infrastructure. This provides an indication about the existing knowledge on the development state of collection/ mining and processing.	0	1	2	3	4
Use of machine and infrastructure	0	1	2	3	4

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
The application of machines and infrastructure. This provides an indication about the efficiency of machines and infrastructure.					
Would you use any additional sub-components to describe technology? (please state)					

5. * In general terms, how important are these sub-components for **economy**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Costs for collection/ mining and processing The monetary amount that has to be spent. This provides an orientation on the costs for collection/ mining and processing of a country.	0	1	2	3	4
Cost volatility for collection/ mining and processing Liability of costs to change rapidly and unpredictably. This provides an indication about the volatility of a market for collection/ mining and processing over the past 5 years.	0	1	2	3	4
Would you use any additional sub-components to describe economy? (please state)					

6. * In general terms, how important are these sub-components for **society**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Social regulatory requirement A rule or directive that provides a framework for social conditions made and maintained by an authority. This provides an orientation on the situation of social regulation and standard enforcement.	0	1	2	3	4
Working conditions Working environment and all existing circumstances affecting labours in the workplace. This provides an orientation on the existing employment and non-fatal occupational injuries at a work place.	0	1	2	3	4
Human rights implications Implications of a right which is believed to belong to every person. This provides an indication about the human rights situation of a country.	0	1	2	3	4
Societal stability Society that is not likely to undergo drastic changes. This provides an indication about the societal situation regarding stability of a country.	0	1	2	3	4
Would you use any additional sub-components to describe society?					

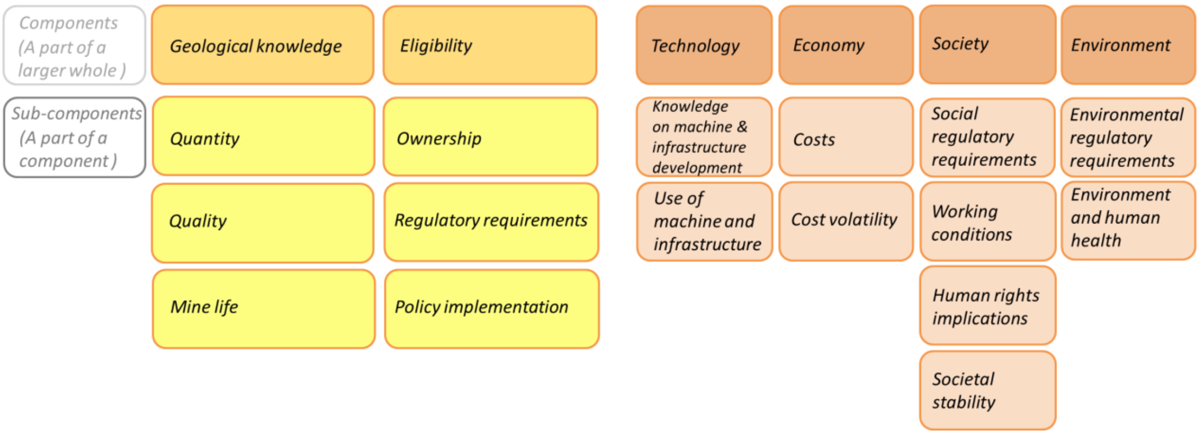
(please state)	

7. * In general terms, how important are these sub-component for **environment**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Environmental regulatory requirement A rule or directive providing a framework for environmental conditions made and maintained by an authority. This provides an orientation on the situation of environmental regulation and standard enforcement.	0	1	2	3	4
Environment and human health An area in the world, which is affected by human activities. This provides an indication of the condition of ecosystems, resource depletion and human health related to collection/ mining and processing.	0	1	2	3	4
Would you use any additional sub-components to describe environment? (please state)					

8. Would you use any additional sub-components? (please state)?

B) Assessing the importance of indicators



Note: each **sub-component** (which acts as an overarching theme) is underpinned by **indicators** (that quantitatively indicate the condition of a status in particular).

Please circle (online-version: click the circle) one value for each indicator and state your reason

Geological knowledge

For your information, there are no questions for this component, since there is only one indicator for each sup-component.

Eligibility

9. * In general terms, how important is this indicator for **regulatory requirement**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Rule of law The ability of a country to abide the quality of contract enforce-	0	1	2	3	4

ment, property rights, and the courts. Measured by world governance indicator, rule of law.					
Operating license A permit from an authority to operate a process, such as collection/ mining and processing. Measured by existing certification about operating license, such as hazardous waste handling or atomic energy licensing board.	0	1	2	3	4
Could you suggest any additional indicators to quantify regulatory requirement? (please state)					

Technology

10. * In general terms, how important are these indicators for the **use of machine and infrastructure**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Annual rate of collection, mining recovery and processing recovery The share of valuable material obtained from collection/ mining or processing (physical and metallurgical separation of either End-of-Life products or ores). Meas-	0	1	2	3	4

ured by these rates.					
Cumulated energy demand Added up energy consumption from collection/ mining or processing. Measured information on cumulated energy demand.	0	1	2	3	4
Exergy The energy required by the best available technology to produce from: an EoL product or rock, a metal to a reference state (starting point, i.e. EoL product or rock). Measured by information on compound and chemical concentration.	0	1	2	3	4
Could you suggest any additional indicators to quantify the use of machine and infrastructure? (please state)					

11. * Which indicator do you consider more important for quantifying the **use of machine and infrastructure**?

	More important
Annual rate of collection/ mining recovery and processing recovery	0
Cumulated energy demand	0
Exergy	0

Note: Online tick with only one answer possible

Economy

For your information there are no questions for this component, since there is only one indicator for each sup-component.

Society

12. * In general terms, how important are these indicators for **working conditions**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Working hours The typical value of hours worked in a job per one week. Measured by international labour organisation, index on hours of work.	0	1	2	3	4
Non-fatal occupational injuries The extent to which workers are protected from work-related hazards and risks. Measured by international labour organisation, index on non-fatal occupational injuries.	0	1	2	3	4
Could you suggest any additional indicators to quantify working conditions at a country level? (please state)					

13. * In general terms, how important are these indicators for **societal stability**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Political stability and absence of violence/terrorism	0	1	2	3	4

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
The possibility of a government to be destabilized or overthrown by unconstitutional or violent means. Measured by world governance indicator, political stability and absence of violence/terrorism.					
Corruption perception The perceived level of public sector corruption of a country. Measured by world governance indicator, control of corruption.	0	1	2	3	4
Could you suggest any additional indicators to quantify societal stability at a country level? (please state)					

Note: in the online version a respond to one answer per question, which cannot be the same to the second question, was activated to ensure there is a differentiation between the two questions

Environment

14. * In general terms, how important are these indicators for **environment and human health**?

	Please circle (online version: click the circle)				
	Not at all important	Not very important	Moderately important	Very important	Extremely important
Ecosystems Impacts on the ecosystems using life cycle impact assessment.	0	1	2	3	4

Measured by the ReCiPe-method (indicator approach for life cycle impact assessment).					
Resource depletion Impacts on the resource depletion using life cycle impact assessment. Measured by the ReCiPe-method (indicator approach for life cycle impact assessment).	0	1	2	3	4
Human health Impacts on the human health using life cycle impact assessment. Measured by the ReCiPe-method (indicator approach for life cycle impact assessment).	0	1	2	3	4
Could you suggest any additional indicators to quantify environment and human health? (please state)					

15. * Which indicators do you consider more important for **environment and human health**?

	More important
Ecosystems	0
Resource depletion	0
Human health	0

Note: Online tick with several answers possible

C) Your background

16. * What is your field of expertise:

    Drop down list: geology, waste management, industrial ecology

    a. Other (please state)

17. * What is your current field of employment?

    Drop down list: academia, private – consultant, private – waste management company, private – mining company, regulatory, local authority, academy, national governance,

    b. Other (please state)

18. What are your years of working experiences?

    Drop down list: None, 0-4, 5-9, 10 – 19, >20

19. * In which countries do you have working experiences?
20. Drop down list of all countries.
21. What metals or End-of-Life products are your field of expertise?
22. What is your age group?

    Drop down list: <18, 18 – 24, 25 – 44, 45 - 64, >65

23. Are you?

    Tick: Female or Male

24. Do you have any additional remarks?

____

____

____

Thank you for participating and sharing your expertise with us!

Note: after having pressed 'Done', please ignore the sign-up request of the next page.

G.4 Framework refinement and confirmation, method: Delphi study questionnaire for round II

In this questionnaire, some of the sub-component and indicator terms were further developed (Table 31). This does not affect the underlying meaning of the terms.

Table 31: Clarification of terms further developed in this paper and as used in the questionnaire for Delphi study round two.

Term further developed	Term as used in the questionnaire
Market concentration	Ownership
Costs for collecting, mining and processing	Costs
Cost volatility for collecting, mining and processing	Cost volatility
Total environmental impacts	Environment and human health
WGI 'rule of law'	Rule of law
Indexed annual rate of collection, mining recovery and processing recovery	Annual rate of collection, mining recovery and processing recovery
Exergy replacement costs	Exergy
Political stability	Political stability and absence of violence/terrorism

Deposits: Evaluating the Accessibility of Scarce Metals from End-of-Life Products and the Earth's Crust

Introduction

An End-of-Life product mine

A geological mine

What is this research about?

This is the second and final survey regarding how to **quantitatively evaluate the accessibility of metals** from End-of-Life (EoL) products and the Earth's crust. This evaluation can be used to provide **an indicator-based early project stage indication** about the development of an 'EoL product mine', which can be compared with a geological mine. Our survey is about **capturing the status of the current mining and processing** and not about your personal opinion. This second inquiry aims to build consensus of your opinion with the groups' opinion. Consequently, these questions are very similar and consist of the following 3 sections, which will require about **20 minutes of your time:**

A) Reassessing the importance of sub-components (an overarching theme)
B) Reassessing the importance of indicators (quantitatively indicating the condition of a status in particular)
C) Your background

Please read the following information carefully.

Please complete your survey by the **29th of May 2017**.

Why have I been chosen?

With your experience in working with evaluation on geology, waste management, industrial ecology, or sustainability assessment you will enhance the quantification of components and sub-components with indicators related to geological knowledge, eligibility, technology, economy, society and environment. This very much supports the understanding of the current raw material accessibility.

What will happen to me if I take part?

You are kindly invited to participate with your expert knowledge in two online survey rounds, with duration of about 20 min for each.

Are there any benefits in my taking part?

Your participation will kindly be rewarded with our general findings of the survey.

Are there any risks involved?

There are minor risks involved. The information that is provided during the survey will be stored on a password protected computer, and only be used for the purpose of this study. Only the results of ranking questions will be published in the PhD thesis and any journal articles arising from this study.

Will my participation be confidential?

Any information provided here will be compliant with the Data Protection Act and confidentiality policies of the University of Southampton. Data will be stored on a password protected computer and will not be disclosed to third parties.

What happens if I change my mind?

You have the right to withdraw at any time without affecting your legal rights.

What happens if something goes wrong?

In the unlikely case of concern or complaint, please refer all correspondence to the Research Governance Manager or the researcher in charge: NAME at the University of Southampton.

For Research Governance Manager please email: E-MAIL address.

For the researcher in charge NAME please email: E-MAIL address

Where can I get more information?

For more information, please contact the principal researcher NAME and E-MAIL address.

*Before commencing this survey, we need you to consent the following items.

1. I have read and understood the information above and have had the opportunity to ask questions about the study.

2. I agree to take part in this research project and agree for my data to be used for the purpose of this study.

3. I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected.

4. I am happy to be contacted regarding other unspecified research projects. I therefore consent to the University retaining my personal details on a database, kept separately from the research data detailed above. The ‘validity’ of my consent is conditional upon the University complying with the Da-

ta Protection Act and I understand that I can request my details be removed from this database at any time.

Data Protection

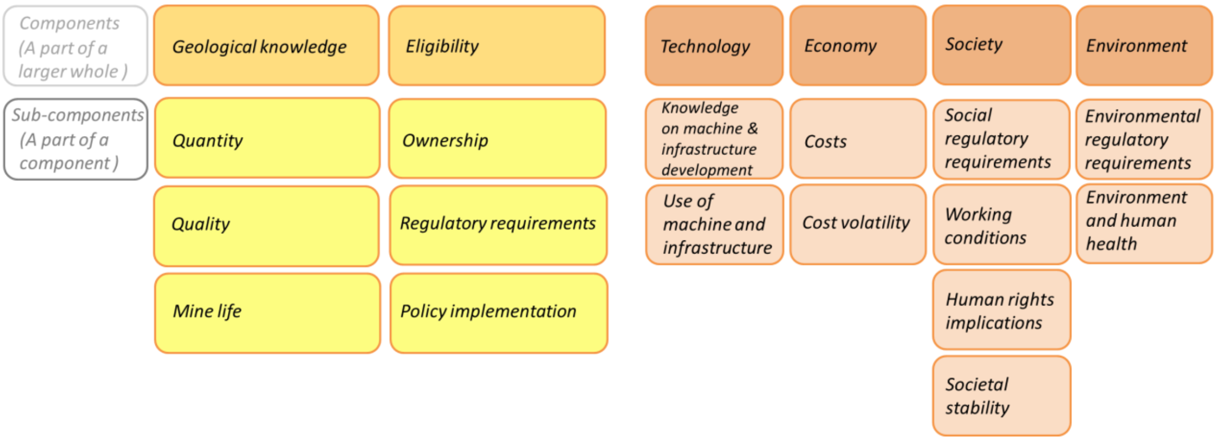
I understand that information collected about me during my participation in this study will be stored on a password protected computer and that this information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Thank you in advance for participating. As a thank you, our general findings will be shared with you.

1. **If you consent the items 1-4, please click 'yes' and then 'Next' at the bottom of this page.**

Circle: yes (Online, tick shown)

A) Reassessing the importance of sub-components



Components (A part of a larger whole)	*Geological knowledge*	*Eligibility*	*Technology*	*Economy*	*Society*	*Environment*
Sub-components (A part of a component)	*Quantity*	*Ownership*	*Knowledge on machine & infrastructure development*	*Costs*	*Social regulatory requirements*	*Environmental regulatory requirements*
	Quality	*Regulatory requirements*	*Use of machine and infrastructure*	*Cost volatility*	*Working conditions*	*Environment and human health*
	Mine life	*Policy implementation*			*Human rights implications*	
					Societal stability	

Please bear the following in mind, while answering these questions**:**

1. You are kindly invited to **consider the groups response** of the three highest choice options (moderately important, very important and extremely important) **and then reassess** the provided sub-components and indicators.
2. This survey considers the **current global mining and processing situation** independent from the sources: 'End-of-Life products' and the 'Earth's crust'.
3. Please respond based on **your experience**.

4. ‘**Accessibility**’ means raw materials are accessible if there are no significant constraints (e.g. financial, technological and environmental restrictions) to ‘get to’ the material of interest in order for potential treatment or production.
5. ‘**Importance**’ means the fact of being of great significance or value.

Please circle (online-version: click the circle) one value for each indicator and state your reason

2. * By considering the groups response, how important are these sub-components for **geological knowledge**?

Group’s response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Quantity	7%	17%	**<u>44%</u>**	33%
Quality	5%	7%	30%	**<u>59%</u>**
Mine life	13%	26%	**<u>41%</u>**	18%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Quantity The annual flow of a material from a deposit containing rock or End-of-Life products. This provides information about the annual mass flow of material collection/ mining and processing.	1	2	3	4
Quality A characteristic of a rock or End-of-Life (EoL) product. This provides an indication on the mass fraction of ore in rock or component in EoL product.	1	2	3	4
Mine life Expected duration of ore production from a	1	2	3	4

mine (operational step: mining) and End-of-Life product generation (operational step: collection). This provides information on the duration of mining, collection and processing from a deposit.				
Would you use any additional sub-components to describe geological knowledge? (please state)				

3. * Which **two** sub-components do you consider more important for **geological knowledge**?

	More important
Quantity	0
Quality	0
Mine life	0

4. * By considering the groups response, how important are these sub-components for **eligibility?**

‘**Eligibility**’ means having the right to do or obtain something and satisfying the appropriate conditions

Group’s response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Ownership	5%	23%	39%	33%
Regulatory requirement	3%	10%	53%	34%
Policy implementation	8%	38%	39%	15%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important

Ownership The state or right of possessing something. This provides an orientation about the clarity of ownership during collection/ mining and processing.	1	2	3	4
Regulatory requirement A rule or directive made and maintained by an authority. This provides an orientation on the quality of contract enforcement and property rights.	1	2	3	4
Policy implementation Principle of action adopted by an organization. This provides an orientation on the attractiveness of implementing mining projects.	1	2	3	4
Would you use any additional sub-components to describe eligibility? (please state)				

5. * Which **two** sub-components do you consider more important for **eligibility**?

	More important
Ownership	0
Regulatory requirement	0
Policy implementation	0

6. * By considering the groups response, how important are these sub-components for **technology**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Knowledge of machine and infra-	7%	34%	<u>44%</u>	13%

structure development				
Use of machine and infrastructure	10%	28%	<u>44%</u>	16%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Knowledge of machine and infrastructure development The information and skills about machines and infrastructure. This provides an indication about the existing knowledge on the development state of collection/ mining and processing.	1	2	3	4
Use of machine and infrastructure The application of machines and infrastructure. This provides an indication about the efficiency of machines and infrastructure.	1	2	3	4
Would you use any additional sub-components to describe technology? (please state)				

7. * By considering the groups response, how important are these sub-components for **economy**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Costs for collection/ mining and processing	0%	10%	<u>52%</u>	38%
Cost volatility for collection/ mining	7%	21%	<u>52%</u>	18%

and processing				

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Costs for collection/ mining and processing The monetary amount that has to be spent. This provides an orientation on the costs for collection/ mining and processing of a country.	1	2	3	4
Cost volatility for collection/ mining and processing Liability of costs to change rapidly and unpredictably. This provides an indication about the volatility of a market for collection/ mining and processing over the past 5 years.	1	2	3	4
Would you use any additional sub-components to describe economy? (please state)				

8. * By considering the groups response, how important are these sub-components for **society**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Social regulatory requirement	7%	38%	34%	18%
Working conditions	12%	26%	41%	20%
Human rights implications	10%	26%	41%	21%
Societal stability	15%	26%	36%	22%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Social regulatory requirement A rule or directive that provides a framework for social conditions made and maintained by an authority. This provides an orientation on the situation of social regulation and standard enforcement.	1	2	3	4
Working conditions Working environment and all existing circumstances affecting labours in the workplace. This provides an orientation on the existing employment and non-fatal occupational injuries at a work place.	1	2	3	4
Human rights implications Implications of a right which is believed to belong to every person. This provides an indication about the human rights situation of a country.	1	2	3	4
Societal stability Society that is not likely to undergo drastic changes. This provides an indication about the societal situation regarding stability of a country.	1	2	3	4
Would you use any additional sub-components to describe society? (please state)				

9. * Which **two** sub-components do you consider more important for **society**?

	More important

Social regulatory requirement	0
Working conditions	0
Human rights implications	0
Societal stability	0

10. * By considering the groups response, how important are these sub-component for **environment**?

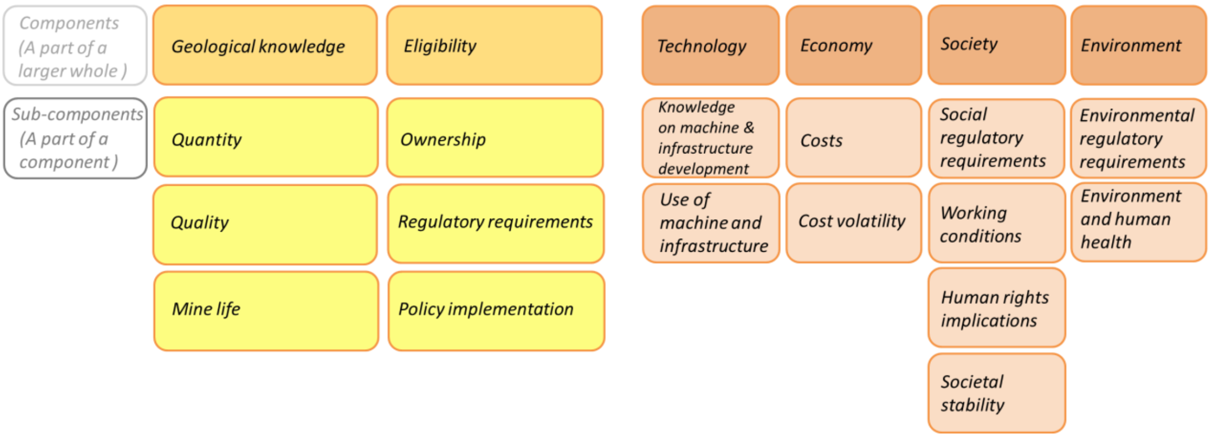
Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Environmental regulatory requirement	2%	18%	**49%**	31%
Environment and human health	5%	18%	**46%**	31%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Environmental regulatory requirement A rule or directive providing a framework for environmental conditions made and maintained by an authority. This provides an orientation on the situation of environmental regulation and standard enforcement.	1	2	3	4
Environment and human health An area in the world, which is affected by human activities. This provides an indication of the condition of ecosystems, resource depletion and human health related to collection/ mining and processing.	1	2	3	4

Would you use any additional sub-components to describe environment? (please state)	

B) Reassessing the importance of indicators



Components (A part of a larger whole)	Geological knowledge	Eligibility	Technology	Economy	Society	Environment
Sub-components (A part of a component)	Quantity	Ownership	Knowledge on machine & infrastructure development	Costs	Social regulatory requirements	Environmental regulatory requirements
	Quality	Regulatory requirements	Use of machine and infrastructure	Cost volatility	Working conditions	Environment and human health
	Mine life	Policy implementation			Human rights implications	
					Societal stability	

Note: each **sub-component** (which acts as an overarching theme) is underpinned by **indicators** (that quantitatively indicate the condition of a status in particular).

Please circle (online-version: click the circle) one value for each indicator and state your reason

Geological knowledge

For your information, there are no questions for this component, since there is only one indicator for each sup-component.

Eligibility

11. * By considering the groups response, how important are these indicators for **regulatory requirement**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important

Rule of law	5%	27%	37%	31%
Operating license	3%	13%	54%	29%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Rule of law The ability of a country to abide the quality of contract enforcement, property rights, and the courts. Measured by world governance indicator, rule of law.	1	2	3	4
Operating license A permit from an authority to operate a process, such as collection/ mining and processing. Measured by existing certification about operating license, such as hazardous waste handling or atomic energy licensing board.	1	2	3	4
Could you suggest any additional indicators to quantify regulatory requirement? (please state)				

12. * Which indicator do you consider more important for **regulatory requirement**?

	More important
Rule of law	0
Operating license	0

Note: Online tick one possible answers

Technology

13. * By considering the groups response, how important are these indicators for the **use of machine and infrastructure**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Annual rate of collection, mining recovery and processing recovery	3%	19%	<u>56%</u>	20%
Cumulated energy demand	14%	32%	<u>45%</u>	7%
Exergy	20%	28%%	<u>36%</u>	10%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Annual rate of collection, mining recovery and processing recovery The share of valuable material obtained from collection/ mining or processing (physical and metallurgical separation of either End-of-Life products or ores). Measured by these rates.	1	2	3	4
Cumulated energy demand Added up energy consumption from collection/ mining or processing. Measured information on cumulated energy demand.	1	2	3	4
Exergy The energy required by the best available technology to produce from: an EoL product or rock, a metal to a reference state (starting	1	2	3	4

point, i.e. EoL product or rock). Measured by information on compound and chemical concentration.				
Could you suggest any additional indicators to quantify the use of machine and infrastructure? (please state)				

14. Which indicator do you consider more important for quantifying the **use of machine and infrastructure**?

	More important
Annual rate of collection/ mining recovery and processing recovery	0
Cumulated energy demand	0
Exergy	0

Note: Online tick with only one answer possible

Economy

For your information there are no questions for this component, since there is only one indicator for each sup-component.

Society

15. * By considering the groups response, how important are these indicators for **working conditions**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Working hours	19%	43%	31%	7%
Non-fatal occupational injuries	3%	14%	48%	36%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very im-portant	Extremely important
Working hours The typical value of hours worked in a job per one week. Measured by international labour organisation, index on hours of work.	1	2	3	4
Non-fatal occupational injuries The extent to which workers are protected from work-related hazards and risks. Measured by international labour organisation, index on non-fatal occupational injuries.	1	2	3	4
Could you suggest any additional indicators to quantify working conditions at a country level? (please state)				

16. * Which indicator do you consider more important for **working conditions**?

	More important
Working hours	0
Non-fatal occupational injuries	0

Note: Online tick one possible answers

17. * By considering the groups response, how important are these indicators for **societal stability**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Political stability and absence of violence/terrorism	0%	19%	**46%**	36%
Corruption perception	7%	37%	**42%**	14%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Political stability and absence of violence/terrorism The possibility of a government to be destabilized or overthrown by unconstitutional or violent means. Measured by world governance indicator, political stability and absence of violence/terrorism.	1	2	3	4
Corruption perception The perceived level of public sector corruption of a country. Measured by world governance indicator, control of corruption.	1	2	3	4
Could you suggest any additional indicators to quantify societal stability at a country				

level? (please state)	

18. * Which indicator do you consider more important for **societal stability**?

	More important
Political stability and absence of violence/terrorism	0
Corruption perception	0

Note: Online tick one possible answers

Environment

19. * By considering the groups response, how important are these indicators for **environment and human health**?

Group's response (the highest values are underlined for you)

	Not very important	Moderately important	Very important	Extremely important
Ecosystems	2%	18%	47%	31%
Resource depletion	17%	20%	36%	17%
Human health	**2%**	**15%**	56%	25%

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important

	Please circle (online version: click the circle)			
	Not very important	Moderately important	Very important	Extremely important
Ecosystems Impacts on the ecosystems using life cycle impact assessment. Measured by the ReCiPe-method (indicator approach for life cycle impact assessment).	1	2	3	4
Resource depletion Impacts on the resource depletion using life cycle impact assessment. Measured by the ReCiPe-method (indicator approach for life cycle impact assessment).	1	2	3	4
Human health Impacts on the human health using life cycle impact assessment. Measured by the ReCiPe-method (indicator approach for life cycle impact assessment).	1	2	3	4
Could you suggest any additional indicators to quantify environment and human health? (please state)				

20. * Which indicators do you consider more important for **environment and human health**?

	More important
Ecosystems	0
Resource depletion	0
Human health	0

Note: Online tick with several answers possible

G.5 Framework consolidation: quantification of indicators

Table 32: Refined sub-component and indicators with their quantification and ranking along operational steps. Note, the ordinal ranking means this indicator was assigned by a number between 0 to 1, 2, or maximal The cells coloured in light grey are related to availability, whereas the cells coloured in white are related to approachability. N/A is not available.

Component	Sub-component	Indicator	Quantification	Reference to identify data values
Geological knowledge	Quantity	Annual mass flow	dM_{oi}= Process inflow (M_i) – process outflow (M_o) for each operational step	USGS, industry; or company reports, books, and scientific papers such as Simoni et al., (2015); Wall, (2014)
	Quality	Mass fraction	“ore” / “material”	USGS, industry; or company reports, books, and scientific papers such as Simoni et al., (2015); Wall, (2014)
Eligibility	Market concentration	Market concentration	$$\mathrm{HHI(c)} = \sum_i (S_{if})^2$$ S_{if} = share of processing countries or collection points and processing companies in one country with a system boundary of a country (Weber and Heinrich, 2012).	(Weber and Heinrich, 2012)
	Regulatory requirement	Operating license	N/A, ordinal ranking	Industry or company reports
Technology	Knowledge of machine and infrastructure development	Knowledge of machine and infrastructure	N/A, ordinal ranking	Scientific papers and technical reports

Component	Sub-component	Indicator	Quantification	Reference to identify data values
	Use of machine and infrastructure	Indexed annual rate of collection, mining recovery and processing recovery	Indexed annual rate of collection, mining recovery and processing recovery * innovation efficiency ratio	Scientific papers, technical reports, and indexes such as INSEAD (2015)
Economy	Costs for collecting, mining and processing	Indexed costs in a country	∑ material price $_{world}$ x share labour costs $_{country}$ x price level $_{country}$	USGS, Trading Economics, OECD iLibrary, technical reports
	Cost volatility for collecting, mining and processing	Indexed cost volatility in a country	∑ (material price $_{world}$ x labour costs $_{country}$ x price level $_{country}$)$_{basis\ year}$ / (material price $_{world}$ x labour costs $_{country}$ x price level $_{country}$) $_{five\ years\ lower\ than\ basis\ year}$	Spörri et al. (2017) USGS, Trading Economics, OECD iLibrary
Society	Working conditions	Non-fatal occupational injuries	Requires further improvement, thus excluded, since the data sources vary in fundamental different specific concepts (ILO, 2017).	(Bach et al., 2017; ILO, 2017)
	Human rights implications	Freedom of speech	WGI-VA $_{country}$	(Tuma et al., 2014; World Bank, 2016)
	Societal stability	Political stability	WGI-PV $_{country}$	(BGS, 2015; Tuma et al., 2014; World Bank, 2016)
Environment	Environmental regulatory requirement	Environmental regulations and standards	N/A, ordinal ranking	Industry or company reports
	Total environmental impacts	Ecosystems and Human health	- Ecosystem: End point category level of ∑ (agricultural land occupation; climate change, ecosystems; freshwater ecotoxicity; - eu-	adapted from Graedel et al., (2012); Spörri et al., (2017); Wolfensberger

Component	Sub-component	Indicator	Quantification	Reference to identify data values
			trophication; marine ecotoxicity; natural land transformation; terrestrial acidification; terrestrial ecotoxicity; and urban land occupation); - Human health: End point category level of ∑(climate change, human health; human toxicity; ionising radiation; ozone depletion; particulate matter formation; and photochemical oxidant formation). (adapted from Graedel et al., 2012; Spörri et al., 2017)	et al., (2015)

G.6 Framework application, results and discussion: overall results and scoring of mining deposits in the anthroposphere and geosphere

Figure 28 Results from quantifying and scoring MDA (mining deposits in the anthroposphere) and MDG (mining deposits in the geosphere) along the operational steps. The ranking bases on HDD sourced from laptops and desktop PC in Switzerland in 2015 along the operational steps: collecting, manual and mechanical processing, metallurgical extraction and refining. ’Lower’ accessibility is in red, ‘moderate’ in orange, ‘higher’ in yellow.

Mining the anthroposphere

Mining at output

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
Geological knowledge	Quantity	Collecting, Switzerland	Switzerland	0.0%	1.6	t Nd	own calculation	Data values partially from 2014 - 2015.
		Collecting, Switzerland	Switzerland	0.0%	1.9	t Nd2O3	own calculation	Data values partially from 2014 - 2015.
	Quality	Collecting, Switzerland	Switzerland	0.01	0.025	% t Nd / t Desktop PC and Laptop	own calculation	Same data sources as for mass calculation.
	Quality	Collecting, Switzerland	Switzerland	0.01	0.03	% t Nd2O3 / t Desktop PC and Laptop	own calculation	Same data sources as for mass calculation.
Eligibility	Market concentration	Collecting, Switzerland	Switzerland	0.01	0.01	-	(Swico Abgabestellen, 2017)	Data values from 2017.
	Operating license	Collecting, Switzerland	Switzerland	1	1	-	(Böni, 2015)	Data value for entire Switzerland.
Technology	Knowledge of machine and infrastructure	Collecting, Switzerland	Switzerland	3	3	-	(Böni, 2015)	Data value for entire Switzerland.
	Indexed annual rate of collection, mining recovery and processing recovery	Collecting, Switzerland	Switzerland	51	51	%	Own calculation	Data values from 2013 to 2015 and innovation efficiency normalised data values to range between 0.5% to 2%.
Economy	Indexed costs to a country	Collecting, Switzerland	Switzerland	1.2%	0.5	$ / kg HDD	Own calculation	Data sources range from 2015 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
	Indexed cost volatility to a country	Collecting, Switzerland	Switzerland	110	110	%	Own calculation	Data sources range from 2011 - 2016. From this source (that includes many

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
								countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
Society	Freedom of speech	Collecting, Switzerland	Switzerland	99	99	%	(World Bank, 2016)	
	Political stability	Collecting, Switzerland	Switzerland	95	95	%	(World Bank, 2016)	
Environment	Environmental regulations and standards	Collecting, Switzerland	Switzerland	1	1	-	(Cenelec 50625-2, 2015)	
	ReCiPe: Ecosystem and Human health	Collecting, Switzerland	Switzerland	0.001129	0.001129	Pt	(Wolfensberger, 2015)	
Mining the geosphere								
Mining at output								
Geological knowledge	Quantity	Mining, Mt. Weld	Australia	1.6%	1992	t Nd2O3	own calculation	Data values from 2013 - 2015.
		Mining, Bayan Obo	China	44.7%	55383	t Nd2O3	own calculation	Data values from 2013 - 2015.
		Mining, Mt. Pass	USA	0.2%	238	t Nd2O3	own calculation	Data values from 2013 - 2015.
	Quality	Mining, Mt. Weld	Australia	2.3	8	% tREO / t material	(Wall, 2014)	Value for REO used as an indication for Nd.
		Mining, Bayan Obo	China	1.1	4	% tREO / t material	(Wall, 2014)	Value for REO used as an indication for Nd.
		Mining, Mt. Pass	USA	2.3	8	% tREO / t material	(Wall, 2014)	Value for REO used as an indication for Nd.
Eligibility	Market concentration	Mining, Mt. Weld	Australia	65	65	-	own calculation	
		Mining, Bayan Obo	China	7170	7170	-	own calculation	Data value for entire China.
		Mining, Mt. Pass	USA	11	11	-	own calculation	
	Operating license	Mining, Mt. Weld	Australia	1	1	-	own calculation	Data values range from 2013 - 2014.
		Mining, Bayan Obo	China	1	1	-	own calculation	Data values range from 2013 - 2014.
		Mining, Mt. Pass	USA	1	1	-	own calculation	Data values range from

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
								2013 - 2014.
Technology	Knowledge of machine and infrastructure	Mining, Mt. Weld	Australia	3	3	-	own calculation	Data values range from 2013 - 2014.
		Mining, Bayan Obo	China	3	3	-	own calculation	Data values range from 2013 - 2014.
		Mining, Mt. Pass	USA	3	3	-	own calculation	Data values range from 2013 - 2014.
	Indexed annual rate of collection, mining recovery and processing recovery	Mining, Mt. Weld	Australia	100	100	%	Sprecher, 2014, SI p. 3	Data values from 2014.
		Mining, Bayan Obo	China	100	100	%	Sprecher, 2014, SI p. 3	Data values from 2014.
		Mining, Mt. Pass	USA	100	100	%	Sprecher, 2014, SI p. 3	Data values from 2014.
Economy	Indexed costs to a country	Mining, Mt. Weld	Australia	NAV	NAV	NAV	NAV	
		Mining, Bayan Obo	China	NAV	NAV	NAV	NAV	
		Mining, Mt. Pass	USA	NAV	NAV	NAV	NAV	
	Indexed cost volatility to a country	Mining, Mt. Weld	Australia	NAV	NAV	NAV	NAV	
		Mining, Bayan Obo	China	NAV	NAV	NAV	NAV	
		Mining, Mt. Pass	USA	NAV	NAV	NAV	NAV	
Society	Freedom of speech	Mining, Mt. Weld	Australia	93	93	%	(World Bank, 2016)	
		Mining, Bayan Obo	China	5	5	%	(World Bank, 2016)	
		Mining, Mt. Pass	USA	81	81	%	(World Bank, 2016)	
	Political stability	Mining, Mt. Weld	Australia	77	77	%	(World Bank, 2016)	
		Mining, Bayan Obo	China	27	27	%	(World Bank, 2016)	
		Mining, Mt. Pass	USA	70	70	%	(World Bank, 2016)	
Environment	Environmental regulations and standards	Mining, Mt. Weld	Australia	1	1	-	(Lynas, 2016)	Data sources range from 1998 - 2016.
		Mining, Bayan Obo	China	0	0	-	-	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.
		Mining, Mt. Pass	USA	1	1	-	(Chevron, 1998)	Data sources range from

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
								1998 - 2016.
	ReCiPe: Ecosystem and Human health	Mining, Mt. Weld	Australia	NAV	NAV	-	-	
		Mining, Bayan Obo	China	0.338087	0.338087	Pt	(Wolfensberger, 2015)	Data value accounts also for mineral processing.
		Mining, Mt. Pass	USA	NAV	NAV	-	-	
Mining the anthroposphere								
Mineral processing at output								
Geological knowledge	Quantity	Manual processing, Switzerland	Switzerland	0.0%	1.47	t Nd	own calculation	Data values partially from 2014 - 2015.
		Mechanical processing, Switzerland	Switzerland	0.0%	0.16	t Nd	own calculation	Data values partially from 2014 - 2015.
		Manual processing, Switzerland	Switzerland	0.0%	1.7	t Nd2O3	own calculation	Data values partially from 2014 - 2015.
		Mechanical processing, Switzerland	Switzerland	0.0%	0.2	t Nd2O3	own calculation	Data values partially from 2014 - 2015.
	Quality	Manual processing and mechanical processing, Switzerland	Switzerland	7.6	27	% tNd / t Nd2Fe14B magnet	own calculation	
	Quality	Manual processing and mechanical processing, Switzerland	Switzerland	8.9	31	% tNd2O3 / t Nd2Fe14B magnet	own calculation	
Eligibility	Market concentration	Manual processing and mechanical processing, Switzerland	Switzerland	83	83	-	(Swico, 2017)	Data from 2013 and 2017 and assumed since dismantlers are employed by the recyclers and in the material flow assessment they are integrated in the recyclers, for the HHI, they were also integrated in the recyclers and not differentiated separately. Marked share is assumed to be equally, since the SWICO recycling system is planning the recycling,

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
								consequently there is no free market (Swico, 2013).
	Operating license	Manual processing and mechanical processing, Switzerland	Switzerland	1	1	-	(Böni, 2015)	Data value for entire Switzerland.
Technology	Knowledge of machine and infrastructure	Manual processing and mechanical processing, Switzerland	Switzerland	1	1	-	(Böni, 2015)	Data value for entire Switzerland.
	Indexed annual rate of collection, mining recovery and processing recovery	Manual processing	Switzerland	91.8	91.8	%	Own calculation	Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Mechanical processing	Switzerland	10.2	10.2	%	Own calculation	Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Economy	Indexed costs to a country	Manual processing and mechanical processing, costs	Switzerland	214%	84.5	Costs aggregated $ / kg magnets	Own calculation	Data sources range from 2015 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
		Mechanical processing costs	Switzerland	0.1%	0.1	Costs aggregated $ / kg magnets	Own calculation	Data sources range from 2015 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
	Indexed cost volatility to a country	Manual processing, costs	Switzerland	110	110	%	Own calculation	Data sources range from 2011 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approxi-

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
								mate Switzerland's labour costs.
		Mechanical processing, costs	Switzerland	110	110	%	Own calculation	Data sources range from 2011 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
Society	Freedom of speech	Manual and mechanical processing, Switzerland	Switzerland	99	99	%	(World Bank, 2016)	
	Political stability	Manual and mechanical processing, Switzerland	Switzerland	95	95	%	(World Bank, 2016)	
	ReCiPe: Ecosystem and Human health	Manual processing, Switzerland	Switzerland	0.599	0.599	Pt	(Wolfensberger, 2015)	
		Mechanical processing, Switzerland	Switzerland	0.815	0.815	Pt	(Wolfensberger, 2015)	
Mining the geosphere								
Mineral processing at output								
Geological knowledge	Quantity	Mineral processing, Mt. Weld	Australia	1.2%	1494	t Nd2O3	own calculation	Data values from 2013 - 2015.
		Mineral processing, Bayan Obo	China	22.3%	27691	t Nd2O3	own calculation	Data values from 2013 - 2015.
		Mineral processing, Mt. Pass	USA	0.2%	214	t Nd2O3	own calculation	Data values from 2013 - 2015.
	Quality	Mineral processing, Mt. Weld	Australia	5.3	18.5	% tNd2O3 / t material	(Jaireth and Hoatson, 2014)	
		Mineral processing, Bayan Obo	China	4.9	17	% tNd2O3 / t material	(Zhi Li, 2014, Machacek 2015)	
		Mineral processing, Mt. Pass	USA	3.4	12	% tNd2O3 / t material	(Habib, 2014)	
Eligibility	Market concentra-	Mineral processing,	Australia	65	65	-	own calculation	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
	tion	Mt. Weld						
		Mineral processing, Bayan Obo	China	7170	7170	-	own calculation	Data value includes entire China.
		Mineral processing, Mt. Pass	USA	11	11	-	own calculation	
	Operating license	Mineral processing, Mt. Weld	Australia	1	1	-	own calculation	Data values range from 2013 - 2014.
		Mineral processing, Bayan Obo	China	1	1	-	own calculation	Data values range from 2013 - 2014.
		Mineral processing, Mt. Pass	USA	1	1	-	own calculation	Data values range from 2013 - 2014.
Technology	Knowledge of machine and infrastructure	Mineral processing, Mt. Weld	Australia	3	3	-	own calculation	Data values range from 2013 - 2014.
		Mineral processing, Bayan Obo	China	3	3	-	own calculation	Data values range from 2013 - 2014.
		Mineral processing, Mt. Pass	USA	3	3	-	own calculation	Data values range from 2013 - 2014.
	Indexed annual rate of collection, mining recovery and processing recovery	Mineral processing, Mt. Weld	Australia	76	76	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Mineral processing, Bayan Obo	China	51	51	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Mineral processing, Mt. Pass	USA	92	92	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Economy	Indexed costs to a country	Mineral processing, Mt. Weld	Australia	3.1%	1.23	$/kg REO, 45%	Own calculation	Data sources from 2014 and 2016.
		Mineral processing, Bayan Obo	China	1.6%	0.65	$/kg REO, 45%	Own calculation	Data sources from 2014 and 2016.
		Mineral processing, Mt. Pass	USA	3.0%	1.20	$/kg REO, 45%	Own calculation	Data sources from 2014 and 2016.
	Indexed cost volatility to a country	Mineral processing, Mt. Weld	Australia	NAV	NAV	NAV	NAV	
		Mineral processing,	China	NAV	NAV	NAV	NAV	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		Bayan Obo						
		Mineral processing, Mt. Pass	USA	NAV	NAV	NAV	NAV	
Society	Freedom of speech	Mineral processing, Mt. Weld	Australia	93	93	%	(World Bank, 2016)	
		Mineral processing, Bayan Obo	China	5	5	%	(World Bank, 2016)	
		Mineral processing, Mt. Pass	USA	81	81	%	(World Bank, 2016)	
	Political stability	Mineral processing, Mt. Weld	Australia	77	77	%	(World Bank, 2016)	
		Mineral processing, Bayan Obo	China	27	27	%	(World Bank, 2016)	
		Mineral processing, Mt. Pass	USA	70	70	%	(World Bank, 2016)	
Environment	Environmental regulations and standards	Mineral processing, Mt. Weld	Australia	1	1	-	(Lynas, 2016)	Data sources range from 1998 - 2016.
		Mineral processing, Bayan Obo	China	0	0	-	-	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.
		Mineral processing, Mt. Pass	USA	1	1	-	(Chevron, 1998)	Data sources range from 1998 - 2016.
	ReCiPe: Ecosystem and Human health	Mineral processing, Mt. Weld	Australia	NAV	NAV	-	-	
		Mineral processing, Bayan Obo	China	0.338087	0.338087	Pt	(Wolfensberger, 2015)	Data value accounts also for mining.
		Mineral processing, Mt. Pass	USA	NAV	NAV	-	-	
Mining the anthroposphere								
Metallurgical extraction at output								
Geological	Quantity	Metallurgical ex-	Switzerland	NAV	NAV	t Nd2O3	(Böni, 2015)	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
knowledge		tracting, manual processing, Switzerland						
		Metallurgical extracting, shredded, Switzerland	Switzerland	NAV	NAV	t Nd2O3	(Böni, 2015)	
		Metallurgical extracting manual processing, Japan	Japan	0.0%	1.5	t Nd2O3	own calculation	
		Metallurgical extracting shredded, Japan	Japan	0.0%	0.2	t Nd2O3	own calculation	
		Metallurgical extracting manual processing, Germany	Germany	0.0%	1.5	t Nd2O3	own calculation	
		Metallurgical extracting shredded, Germany	Germany	0.0%	0.2	t Nd2O3	own calculation	
		Metallurgical extracting manual processing, Austria	Austria	0.0%	1.5	t Nd2O3	own calculation	
		Metallurgical extracting shredded, Austria	Austria	0.0%	0.2	t Nd2O3	own calculation	
		Metallurgical extracting manual processing, Vietnam	Vietnam	0.0%	1.5	t Nd2O3	own calculation	
		Metallurgical extracting shredded, Vietnam	Vietnam	0.0%	0.2	t Nd2O3	own calculation	
	Quality	Metallurgical extracting, Switzerland	Switzerland	NAV	NAV	-	(Böni, 2015)	
	Quality	Metallurgical extracting, Japan	Japan	24.3	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al., 2015)	Since no value was available and the processes are the same, the values of geogenic mining were used.
		Metallurgical extracting, Germany	Germany	24.3	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al., 2015)	Since no value was available and the processes are the same, the values of geogenic mining were used.
		Metallurgical extracting, Austria	Austria	24.3	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al.,	Since no value was available and the processes are

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
							2015)	the same, the values of geogenic mining were used.
		Metallurgical extracting, Vietnam	Vietnam	24.3	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al., 2015)	Since no value was available and the processes are the same, the values of geogenic mining were used.
Eligibility	Market concentration	Metallurgical extracting, Switzerland	Switzerland	NAV	NAV	-	(Böni, 2015)	
		Metallurgical extracting, Japan	Japan	NAV	NAV	-	(Bunge, 2015)	
		Metallurgical extracting, Germany	Germany	NAV	NAV	-	(Bunge, 2015)	
		Metallurgical extracting, Austria	Austria	NAV	NAV	-	(Bunge, 2015)	
		Metallurgical extracting, Vietnam	Vietnam	NAV	NAV	-	(Bunge, 2015)	
	Operating license	Metallurgical extracting, Switzerland	Switzerland	NAV	NAV	-	(Böni, 2015)	
		Metallurgical extracting, Japan	Japan	1	1	-	(Bunge, 2015)	Data value for entire Japan.
		Metallurgical extracting, Germany	Germany	1	1	-	(Bunge, 2015)	Data value for entire Germany.
		Metallurgical extracting, Austria	Austria	1	1	-	(Bunge, 2015)	Data value for entire Austria.
		Metallurgical extracting, Vietnam	Vietnam	1	1	-	(Bunge, 2015)	Data value for entire Vietnam.
Technology	Knowledge of machine and infrastructure	Metallurgical extracting, Switzerland	Switzerland	0	0	-	(Bunge, 2015)	Data value for entire Switzerland.
		Metallurgical extracting, Japan	Japan	3	3	-	(Bunge, 2015)	Data value for entire Japan.
		Metallurgical extracting, Germany	Germany	3	3	-	(Bunge, 2015)	Data value for entire Germany.
		Metallurgical extracting, Austria	Austria	3	3	-	(Bunge, 2015)	Data value for entire Austria.
		Metallurgical extracting, Vietnam	Vietnam	3	3	-	(Bunge, 2015)	Data value for entire Vietnam.
	Indexed annual rate of collection, mining recovery and processing recovery	Metallurgical extracting, manual, Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Metallurgical ex-	Switzerland	NAV	NAV	-	(Bunge, 2015)	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		tracting, mechanical (mechanical processing), Switzerland						
		Metallurgical extracting, Japan	Japan	91	91	%	Own calculation	Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Metallurgical extracting, Germany	Germany	92	92	%	Own calculation	Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Metallurgical extracting, Austria	Austria	91	91	%	Own calculation	Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Metallurgical extracting, Vietnam	Vietnam	91	91	%	Own calculation	Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Economy	Indexed costs to a country	Metallurgical extracting, manual, Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Metallurgical extracting, mechanical (mechanical processing), Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Metallurgical extracting, Japan	Japan	NAV	NAV	'-	'-	
		Metallurgical extracting, Germany	Germany	NAV	NAV	'-	'-	
		Metallurgical extracting, Austria	Austria	NAV	NAV	'-	'-	
		Metallurgical extracting, Vietnam	Vietnam	NAV	NAV	'-	'-	
	Indexed cost volatility to a country	Metallurgical extracting, manual, Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Metallurgical extracting, mechanical	Switzerland	NAV	NAV	-	(Bunge, 2015)	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		(shredding), Switzerland						
		Metallurgical extracting, Japan	Japan	NAV	NAV	'-	'-	
		Metallurgical extracting, Germany	Germany	NAV	NAV	'-	'-	
		Metallurgical extracting, Austria	Austria	NAV	NAV	'-	'-	
		Metallurgical extracting, Vietnam	Vietnam	NAV	NAV	'-	'-	
Society	Freedom of speech	Metallurgical extracting, Switzerland	Switzerland	NAV	NAV	0	0	
		Metallurgical extracting, Japan	Japan	79	79	%	(World Bank, 2016)	
		Metallurgical extracting, Germany	Germany	96	96	%	(World Bank, 2016)	
		Metallurgical extracting, Austria	Austria	95	95	%	(World Bank, 2016)	
		Metallurgical extracting, Austria	Vietnam	11	11	%	(World Bank, 2016)	
	Political stability	Metallurgical extracting, Switzerland	Switzerland	NAV	NAV	-	0	
		Metallurgical extracting, Japan	Japan	82	82	%	(World Bank, 2016)	
		Metallurgical extracting, Germany	Germany	70	70	%	(World Bank, 2016)	
		Metallurgical extracting, Austria	Austria	90	90	%	(World Bank, 2016)	
		Metallurgical extracting, Vietnam	Vietnam	49	49	%	(World Bank, 2016)	
Environment	Environmental regulations and standards	Metallurgical extracting, Switzerland	Switzerland	NAV	NAV	-	0	Data sources range from 1998 - 2017.
		Metallurgical extracting, Japan	Japan	1	1	-	(Hitachi, 2017)	Data sources range from 1998 - 2017.
		Metallurgical extracting, Germany	Germany	1	1	-	(Loser Chemie, 2017)	Data sources range from 1998 - 2017.
		Metallurgical extracting, Austria	Austria	1	1	-	(Chevron, 1998)	Data sources range from 1998 - 2017.
		Metallurgical extracting, Vietnam	Vietnam	0	0	-	-	Data sources range from 1998 - 2017. No information online available,

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
				🟥				thus assumed to have no certification for environmental standards.
	ReCiPe: Ecosystem and Human health	Metallurgical extracting, manual, Switzerland	Switzerland	NAV	NAV	-	-	
		Metallurgical extracting, mechanical (shredding), Switzerland	Switzerland	NAV	NAV	-	-	Data value accounts also for refining.
		Metallurgical extracting, Japan	Japan	NAV	NAV	-	-	
		Metallurgical extracting, Germany	Germany	NAV	NAV	-	-	
		Metallurgical extracting, Austria	Austria	NAV	NAV	-	-	
		Metallurgical extracting, Vietnam	Vietnam	NAV	NAV	-	-	

Mining the geosphere

Metallurgical extraction at output

Component	**Indicator**	Process step	Location		Quantification	Unit	Reference	Assumption
Geological knowledge	Quantity	Metallurgical extracting, Mt. Weld	Malaysia	0.5%	644	t Nd2O3	own calculation	Data values from 2013 - 2015.
		Metallurgical extracting Bayan Obo	China	16.1%	19938	t Nd2O3	own calculation	Data values from 2013 - 2015.
		Metallurgical extracting Mt. Pass	USA	0.2%	197	t Nd2O3	own calculation	Data values from 2013 - 2015.
	Quality	Metallurgical extraction, Mt. Weld and Malaysia	Malaysia	24.3	85	% tREO / t material	(Simoni, 2015)	Value for REO used as an indication for Nd.
		Metallurgical extraction, Bayan Obo	China	24.3	85	% tREO / t material	(Simoni, 2015)	Value for REO used as an indication for Nd.
		Metallurgical extraction, Mt. Pass	USA	24.3	85	% tREO / t material	(Simoni, 2015)	Value for REO used as an indication for Nd.
Eligibility	Market concentration	Metallurgical extraction, Mt. Weld and	Malaysia	68	68	-	own calculation	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		Malaysia						
		Metallurgical extraction, Bayan Obo	China	7170	7170	-	own calculation	Data value includes entire China.
		Metallurgical extraction, Mt. Pass	USA	11	11	-	own calculation	
	Operating license	Metallurgical extracting, Mt. Weld	Malaysia	1	1	-	own calculation	Data values range from 2013 - 2014.
		Metallurgical extracting Bayan Obo	China	1	1	-	own calculation	Data values range from 2013 - 2014.
		Metallurgical extracting Mt. Pass	USA	1	1	-	own calculation	Data values range from 2013 - 2014.
Technology	Knowledge of machine and infrastructure	Metallurgical extracting, Mt. Weld	Malaysia	3	3	-	own calculation	Data values range from 2013 - 2014.
		Metallurgical extracting Bayan Obo	China	3	3	-	own calculation	Data values range from 2013 - 2014.
		Metallurgical extracting Mt. Pass	USA	3	3	-	own calculation	Data values range from 2013 - 2014.
	Indexed annual rate of collection, mining recovery and processing recovery	Metallurgical extracting, Mt. Weld	Malaysia	91	91	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Metallurgical extracting Bayan Obo	China	73	73	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Metallurgical extracting Mt. Pass	USA	93	93	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Economy	Indexed costs to a country	Metallurgical extracting, Mt. Weld	Malaysia	2.2%	0.87	$/kg REO, 20-70%	Own calculation	Data sources from 2013 to 2016. Since 2015 is after the REE crisis, values from 2009 (before the crisis) were used.
		Metallurgical extracting Bayan Obo	China	5.1%	2.02	$/kg REO, 20-70%	Own calculation	Data sources from 2013 to 2016. Since 2015 is after the REE crisis, values from 2009 (before the crisis)

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
								were used.
		Metallurgical extracting Mt. Pass	USA	16.1%	6.36	$/kg REO, 20-70%	Own calculation	Data sources from 2013 to 2016. Since 2015 is after the REE crisis, values from 2009 (before the crisis) were used.
	Indexed cost volatility to a country	Metallurgical extracting, Mt. Weld	Malaysia	143	143	%	Own calculation	Data sources from 2013 to 2017. Since 2015 is after the REE crisis, values from 2005 and 2009 (before the crisis) were used.
		Metallurgical extracting Bayan Obo	China	125	125	%	Own calculation	Data sources from 2013 to 2017. Since 2015 is after the REE crisis, values from 2005 and 2009 (before the crisis) were used.
		Metallurgical extracting Mt. Pass	USA	168	168	%	Own calculation	Data sources from 2013 to 2017. Since 2015 is after the REE crisis, values from 2005 and 2009 (before the crisis) were used.
Society	Freedom of speech	Metallurgical extracting, Mt. Weld	Malaysia	36	36	%	(World Bank, 2016)	
		Metallurgical extracting Bayan Obo	China	5	5	%	(World Bank, 2016)	
		Metallurgical extracting Mt. Pass	USA	81	81	%	(World Bank, 2016)	
	Political stability	Metallurgical extracting, Mt. Weld	Malaysia	54	54	%	(World Bank, 2016)	
		Metallurgical extracting Bayan Obo	China	27	27	%	(World Bank, 2016)	
		Metallurgical extracting Mt. Pass	USA	70	70	%	(World Bank, 2016)	
Environment	Environmental regulations and standards	Metallurgical extracting, Mt. Weld	Malaysia	1	1	-	(Lynas, 2016)	Data sources range from 1998 - 2016.
		Metallurgical extracting Bayan Obo	China	0	0	-	-	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		Metallurgical extracting Mt. Pass	USA	1	1	-	(Chevron, 1998)	Data sources range from 1998 - 2016.
	ReCiPe: Ecosystem and Human health	Metallurgical extracting, Mt. Weld	Malaysia	NAV	NAV	-	-	
		Metallurgical extracting Bayan Obo	China	2.658851521	2.658851521	Pt	(Wolfensberger, 2015)	Data value accounts also for refining.
		Metallurgical extracting Mt. Pass	USA	NAV	NAV	-	-	
Mining the anthroposphere								
Refining at output								
Geological knowledge	Quantity	Refining, manual processing, Switzerland	Switzerland	NAV	NAV	t Nd2O3	(Böni, 2015)	
		Refining, mechanical processing, Switzerland	Switzerland	NAV	NAV	t Nd2O3	(Böni, 2015)	
		Refining manual processing, Japan	Japan	0.0%	1.4	t Nd2O3	own calculation	
		Refining mechanical processing, Japan	Japan	0.0%	0.2	t Nd2O3	own calculation	
		Refining manual processing, Germany	Germany	0.0%	1.4	t Nd2O3	own calculation	
		Refining mechanical processing, Germany	Germany	0.0%	0.2	t Nd2O3	own calculation	
		Refining manual processing, Austria	Austria	0.0%	1.4	t Nd2O3	own calculation	
		Refining mechanical processing, Austria	Austria	0.0%	0.2	t Nd2O3	own calculation	
		Refining manual processing, Vietnam	Vietnam	0.0%	1.4	t Nd2O3	own calculation	
		Refining mechanical processing, Vietnam	Vietnam	0.0%	0.2	t Nd2O3	own calculation	
	Quality	Refining, Switzerland	Switzerland	NAV	NAV	-	(Böni, 2015)	
	Quality	Refining , Japan	Japan	28.4	99.5	% tNd2O3 / t material	(USGS, 2016)	Since no value was available and the processes are the same, the values of geogenic mining were used.

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		Refining , Germany	Germany	28.4	99.5	% tNd2O3 / t material	(USGS, 2016)	Since no value was available and the processes are the same, the values of geogenic mining were used.
		Refining , Austria	Austria	28.4	99.5	% tNd2O3 / t material	(USGS, 2016)	Since no value was available and the processes are the same, the values of geogenic mining were used.
		Refining , Japan	Vietnam	28.4	99.5	% tNd2O3 / t material	(USGS, 2016)	Since no value was available and the processes are the same, the values of geogenic mining were used.
Eligibility	Market concentration	Refining, Switzerland	Switzerland	NAV	NAV	-	(Böni, 2015)	
		Refining, Japan	Japan	NAV	NAV	-	(Bunge, 2015)	
		Refining, Germany	Germany	NAV	NAV	-	(Bunge, 2015)	
		Refining, Austria	Austria	NAV	NAV	-	(Bunge, 2015)	
		Refining, Vietnam	Vietnam	NAV	NAV	-	(Bunge, 2015)	
	Operating license	Refining, Switzerland	Switzerland	NAV	NAV	-	(Böni, 2015)	
		Refining, Japan	Japan	1	1	-	(Bunge, 2015)	Data value for entire Japan.
		Refining, Germany	Germany	1	1	-	(Bunge, 2015)	Data value for entire Germany.
		Refining, Austria	Austria	1	1	-	(Bunge, 2015)	Data value for entire Austria.
		Refining, Vietnam	Vietnam	1	1	-	(Bunge, 2015)	Data value for entire Vietnam.
Technology	Knowledge of machine and infrastructure	Refining, Switzerland	Switzerland	0	0	-	(Bunge, 2015)	Data value for entire Switzerland
		Refining, Japan	Japan	3	3	-	(Bunge, 2015)	Data value for entire Japan.
		Refining, Germany	Germany	3	3	-	(Bunge, 2015)	Data value for entire Germany.
		Refining, Austria	Austria	3	3	-	(Bunge, 2015)	Data value for entire Austria.
		Refining, Vietnam	Vietnam	3	3	-	(Bunge, 2015)	Data value for entire Vietnam.
	Indexed annual rate of collection, mining recovery and processing recovery	Refining, manual, Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Refining, mechanical	Switzerland	NAV	NAV	-	(Bunge, 2015)	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		(mechanical processing), Switzerland						
		Refining, Japan	Japan	91	91	%	Own calculation	Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Refining, Germany	Germany	92	92	%	Own calculation	Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Refining, Austria	Austria	91	91	%	Own calculation	Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Refining, Vietnam	Vietnam	91	91	%	Own calculation	Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Economy	Indexed costs to a country	Refining, manual, Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Refining, mechanical (mechanical processing), Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Refining, Japan	Japan	118%	46	\$/kg Nd_2O_3	Own calculation	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
		Refining, Germany	Germany	101%	40	\$/kg Nd_2O_4	Own calculation	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congru-

Component	**Indicator**	**Process step**	**Location**	**Quantification with ranking**	**Quantification**	**Unit**	**Reference**	**Assumption**
				🟥				ently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
		Refining, Austria	Austria	🟥 105%	41	$/kg Nd2O5	Own calculation	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
		Refining, Vietnam	Vietnam	🟨 31%	12	$/kg Nd2O6	Own calculation	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
	Indexed cost volatility to a country	Refining, manual, Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Refining, mechanical (shredding), Switzerland	Switzerland	NAV	NAV	-	(Bunge, 2015)	
		Refining, Japan	Japan	🟨 98	98	%	%	Data sources range from 2011 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
		Refining, Germany	Germany	🟧 101	101	%	%	Data sources range from 2011 - 2016. From the labour costs source (that includes many countries)

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
								South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
		Refining, Austria	Austria	99	99	%	%	Data sources range from 2011 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
		Refining, Vietnam	Vietnam	134	134	%	%	Data sources range from 2011 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Society	Freedom of speech	Refining, Switzerland	Switzerland	NAV	NAV	-	-	
		Refining, Japan	Japan	79	79	%	(World Bank, 2016)	
		Refining, Germany	Germany	96	96	%	(World Bank, 2016)	
		Refining, Austria	Austria	95	95	%	(World Bank, 2016)	
		Refining, Vietnam	Vietnam	11	11	%	(World Bank, 2016)	
	Political stability	Refining, Switzerland	Switzerland	NAV	NAV	%	-	
		Refining, Japan	Japan	82	82	%	(World Bank, 2016)	
		Refining, Germany	Germany	70	70	%	(World Bank, 2016)	
		Refining, Austria	Austria	90	90	%	(World Bank, 2016)	
		Refining, Vietnam	Vietnam	49	49	%	(World Bank, 2016)	
Environment	Environmental regulations and standards	Refining, Switzerland	Switzerland	NAV	NAV	-	-	Data sources range from 1998 - 2017.
		Refining, Japan	Japan	1	1	-	(Hitachi, 2017)	Data sources range from 1998 - 2017.

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		Refining, Germany	Germany	1	1	-	(Loser Chemie, 2017)	Data sources range from 1998 - 2017.
		Refining, Austria	Austria	1	1	-	(Chevron, 1998)	Data sources range from 1998 - 2017.
		Refining, Vietnam	Vietnam	0	0	-	-	Data sources range from 1998 - 2017. No information online available, thus assumed to have no certification for environmental standards.
	ReCiPe: Ecosystem and Human health	Refining, manual, Switzerland	Switzerland	NAV	NAV	-	-	Data value accounts also for metallurgical extracting.
		Refining, mechanical (shredding), Switzerland	Switzerland	NAV	NAV	-	-	Data value accounts also for metallurgical extracting.
		Refining, Japan	Japan	NAV	NAV	-	-	
		Refining, Germany	Germany	NAV	NAV	-	-	
		Refining, Austria	Austria	NAV	NAV	-	-	
		Refining, Vietnam	Vietnam	NAV	NAV	-	-	
Mining the geosphere								
Refined at output								
Geological knowledge	Quantity	Refining, Mt. Pass	Malaysia	0.5%	580	t Nd2O3	own calculation	Data values from 2014 - 2015.
		Refining, Bayan Obo	China	14.5%	17944	t Nd2O3	own calculation	Data values from 2014 - 2015.
		Refining, Mt. Pass	USA	0.1%	177	t Nd2O3	own calculation	Data values from 2014 - 2015.
	Quality	Refining, Mt. Weld	Malaysia	28.4	99.5	% tNd2O3 / t material	(USGS, 2016)	
		Refining, Bayan Obo	China	28.4	99.5	% tNd2O3 / t material	(USGS, 2016)	
		Refining, Mt. Pass	USA	28.4	99.5	% tNd2O3 / t material	(USGS, 2016)	
Eligibility	Market concentration	Refining, Mt. Weld	Malaysia	68	68	-	own calculation	
		Refining, Bayan Obo	China	7170	7170	-	own calculation	Data value for entire China.
		Refining, Mt. Pass	USA	11	11	-	own calculation	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
	Operating license	Refining, Mt. Weld	Malaysia	1	1	-	own calculation	Data values range from 2013 - 2014.
		Refining, Bayan Obo	China	1	1	-	own calculation	Data values range from 2013 - 2014.
		Refining, Mt. Pass	USA	1	1	-	own calculation	Data values range from 2013 - 2014.
Technology	Knowledge of machine and infrastructure	Refining, Mt. Weld	Malaysia	3	3	-	(Schmidt, 2013)	Data values range from 2013 - 2014.
		Refining, Bayan Obo	China	3	3	-	(Wübbeke, 2013)	Data values range from 2013 - 2014.
		Refining, Mt. Pass	USA	3	3	-	(Machacek and Fold, 2014)	Data values range from 2013 - 2014.
	Indexed annual rate of collection, mining recovery and processing recovery	Refining, Mt. Pass	Malaysia	91	91	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Refining, Bayan Obo	China	91	91	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
		Refining, Mt. Pass	USA	91	91	%	Own calculation	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Economy	Indexed costs to a country	Refining, Mt. Pass	Malaysia	116%	46	\$/kg Nd2O3	Own calculation	
		Refining, Bayan Obo	China	61%	24	\$/kg Nd2O4	Own calculation	
		Refining, Mt. Pass	USA	117%	46	\$/kg Nd2O5	Own calculation	
	Indexed cost volatility to a country	Refining, Mt. Weld	Malaysia	16	16	%	Own calculation	Data values from 2011 and 2015.
		Refining, Bayan Obo	China	22	22	%	Own calculation	Data values from 2011 and 2015. Labour costs value was only available from 2012.
		Refining, Mt. Pass	USA	25	25	%	Own calculation	Data values from 2011 and 2015.
Society	Freedom of speech	Refining, Mt. Weld	Malaysia	36	36	%	(World Bank, 2016)	
		Refining, Bayan Obo	China	5	5	%	(World Bank, 2016)	

Component	Indicator	Process step	Location	Quantification with ranking	Quantification	Unit	Reference	Assumption
		Refining, Mt. Pass	USA	81	81	%	(World Bank, 2016)	
	Political stability	Refining, Mt. Weld	Malaysia	54	54	%	(World Bank, 2016)	
		Refining, Bayan Obo	China	27	27	%	(World Bank, 2016)	
		Refining, Mt. Pass	USA	70	70	%	(World Bank, 2016)	
Environment	Environmental regulations and standards	Refining, Mt. Weld	Malaysia	1	1	-	(Lynas, 2016)	Data sources range from 1998 - 2016.
		Refining, Bayan Obo	China	0	0	-	-	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.
		Refining, Mt. Pass	USA	1	1	-	(Chevron, 1998)	Data sources range from 1998 - 2016.
	ReCiPe: Ecosystem and Human health	Refining, Mt. Weld	Malaysia	NAV	NAV	-		
		Refining, Bayan Obo	China	2.7	2.7	Pt	(Wolfensberger, 2015)	Data value accounts also for metallurgical extracting.
		Refining, Mt. Pass	USA	NAV	NAV	-		

G.7 Framework application, results and discussion: detailed quantification of mining deposits in the geosphere

Figure 29: Results from quantifying MDG (mining deposits in the geosphere) for Nd_2O_3 from Earth's crust along the operational steps. Note: the masses are always output masses of one process and are here equivalent to the input passes of the next process.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Mining													
Geological knowledge													

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Quantity													
Mining, Mt. Weld	Australia	1992	t Nd2O3	own calculation	Quantity Concentrate AUS Nd2O3 per annum	AUS	1494	t Nd_2O_3			Own calculation		Data values from 2013 - 2015.
Mining, Bayan Obo	China	55383	t Nd2O3	own calculation	Quantity Concentrate CN Nd2O3, 2015	CN	27691	t Nd_2O_3			Own calculation		Data values from 2013 - 2015.
Mining, Mt. Pass	USA	238	t Nd2O3	own calculation	Quantity Concentrate USA Nd2O3, 2015	USA	214	t Nd_2O_3			Own calculation		Data values from 2013 - 2015.
					Recovery rate mineral processing (beneficiation)	AUS, Mt. Weld	75	%			Talens Peiró, 2013, p. 1338		
					Recovery rate mineral processing (beneficiation)	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	50	%			Talens Peiró, 2013, p. 1338		
					Recovery rate mineral processing (beneficiation)	USA, Mt Pass	90	%			Talens Peiró, 2013, p. 1338		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Mass fraction													
Mining, Mt. Weld	Australia	8	% tREO / t material	(Wall, 2014)							Verified with >5% (Simoni et al. 2015)	Value for REO used as an indication for Nd.	
Mining, Bayan Obo	China	4	% tREO / t material	(Wall, 2014)								Value for REO used as an indication for Nd.	
Mining, Mt. Pass	USA	8	% tREO / t material	(Wall, 2014)								Value for REO used as an indication for Nd.	
Eligibility													
Market concentration													
Mining, Mt. Weld	Australia	65.0	-	Own calculation	Mining amount REO	Mt. Weld, resp. Australia to world	10000	t	USGS, 2016, p. 135			Explanation: formulisation Σ (a2), e.g. with one supplier --> a market share from 100%: (1x100^2) = 10'000 (Weber und Heinrich, 2012)	
Mining, Bayan Obo	China	7170.3	-	Own calculation	Mining amount	China to world	105000	t	USGS, 2016, p. 135			Data value for entire China.	
Mining, Mt. Pass	USA	10.9	-	Own calculation	Mining amount	USA to world	4100	t	USGS, 2016, p. 135			Note, this value does not take into account the 40% illegal smuggling rate from China (Machacek et al. 2015)	
					Mining amount	World total (rounded)	124000	t	USGS, 2016, p. 135				Quality control: value compared with Nasser, 2015 and are in a similar range.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					Mining Share	Mt. Weld. To world total	8.1	%	own calculation				
						China to world	84.7	%	own calculation				
						USA to world	3.3	%	own calculation				
Operating license													
Mining, Mt. Weld	Australia	1	-	(Schmidt, 2013)								1' means existing operating license, whereas '0' non-existing operating license.	Data values range from 2013 - 2014.
Mining, Bayan Obo	China	1	-	(Wübbeke, 2013)									Data values range from 2013 - 2014.
Mining, Mt. Pass	USA	1	-	(Machacek and Fold, 2014)									Data values range from 2013 - 2014.
Technology													
Knowledge of machine and infrastructure													
Mining, Mt. Weld	Australia	3	-	(Schmidt, 2013)								Quantify: whether knowledge does not exists (0), is in research (1) or scale up-phase (2) or large scale production (3).	Data values range from 2013 - 2014.
Mining, Bayan Obo	China	3	-	(Wübbeke, 2013)									Data values range from 2013 - 2014.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Mining, Mt. Pass	USA	3	-	(Machacek and Fold, 2014)									Data values range from 2013 - 2014.
Indexed annual rate of collection, mining recovery and processing recovery													
Mining, Mt. Weld	Australia	100	%	Sprecher, 2014, SI p. 3									Data values from 2014.
Mining, Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	100	%	Sprecher, 2014, SI p. 3									Data values from 2014.
Mining, Mt. Pass	USA, Mt Pass	100	%	Sprecher, 2014, SI p. 3									Data values from 2014.
Economy													
Indexed costs in a country													
Mining, Mt. Weld	Australia	N/A	N/A	N/A	Bastnäsite concentrate REO with Nd_2O_3 ~70-85%	China	N/A						no prices available, because the concentration of > 5% does not seem to be traded… Prices as N/A (Not

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					costs								available)
Mining, Bayan Obo	China	N/A	N/A	N/A	Monazite concentrate REO with Nd2O3 ~70-85% costs		N/A						
Mining, Mt. Pass	USA	N/A	N/A	N/A	Labour costs	Australia	1.001	decimal	100.1	%	Trading Economics, 2016		
						China	1.036	decimal	103.6	%	Trading Economics, 2016		
						USA	1.101	decimal	110.1	%	Trading Economics, 2016		
					Price level	Australia	1.25	decimal	125	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						China	0.64	decimal	64	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						USA	1.11	decimal	111	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
Indexed cost volatility in a country													
Mining, Mt. Weld	Australia	N/A	N/A	N/A	Bastnäsite concentrate REO with Nd2O3 ~70-85% costs	China	N/A						no prices available, because the concentration of > 5% does not seem to be traded… Prices as N/A (Not available)
Mining, Bayan Obo	China	N/A	N/A	N/A	Monazite concentrate REO	N/A							

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					with Nd2O3 ~70-85% costs								
Mining, Mt. Pass	USA	N/A	N/A	N/A	Labour costs	Australia	1.001	decimal	100.1	%	Trading Economics, 2016		
						China	1.036	decimal	103.6	%	Trading Economics, 2016		
						USA	1.101	decimal	110.1	%	Trading Economics, 2016		
					Price level	Australia	1.25	decimal	125	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						China	0.64	decimal	64	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						USA	1.11	decimal	111	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
Society													
Working Conditions													
Human rights implications													
Freedom of speech													
Mining, Mt. Weld	Australia	93	%	(World Bank, 2016)								Indicator: WGI: Voice and Accountability (VA), 2015 data; Unit:	

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Mining, Bayan Obo	China	5	%	(World Bank, 2016)									
Mining, Mt. Pass	USA	81	%	(World Bank, 2016)									
Societal stability													
Political stability													
Mining, Mt. Weld	Australia	77	%	(World Bank, 2016)								Indicator: WGI: political stability and absence of violence/terrorism, 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Mining, Bayan Obo	China	27	%	(World Bank, 2016)									Since exclusively data for Europe was available Finland was used to proximate Japan; congruently Hungary to proximate Vietnam.
Mining, Mt. Pass	USA	70	%	(World Bank, 2016)									
Environment													

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Environmental regulatory requirement													
Environmental regulations and standards													
Mining, Mt. Weld	Australia	1	-	(Lynas, 2016)								1' means existing environmental regulations and standards, such as ISO 14001, whereas '0' non-existing environmental regulations and standards.	
Mining, Bayan Obo	China	0	-	-								Online search resulted in no confirmation, consequently it is assumed Bayan Obo is not certified, as in the certification it is stated that the certificate needs to be accessibly by the public	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.
Mining, Mt. Pass	USA	1	-	(Chevron, 1998)									Data sources range from 1998 - 2016.
Total environmental impacts													
ReCiPe: Ecosystem and Human health													

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Mining, Mt. Weld	Australia	N/A	-	-									
Mining, Bayan Obo	China	0.338	Pt	(Wolfensberger, 2015)								Value accounts also for mineral processing	Data value accounts also for mineral processing.
Mining, Mt. Pass	USA	N/A	-	-									
Mineral Processing	Masses are always output masses of one process.												
Geological knowledge													
Quantity													
Mineral processing, Mt. Weld	Australia	1494	t Nd_2O_3	own calculation	AUS first half concentrate, 2015	AUS	5263	t REO			(Lynas, 2015 Annual Report, p. 10)		Data values from 2013 - 2015.
Mineral processing, Bayan Obo	China	27691	t Nd_2O_3	own calculation	AUS second half concentrate, 2015	AUS	2811	t REO			(Lynas, 2016 First Half Financial Report, p. 3, assuming that all batched and ready for production volume was produced into REO)		Data values from 2013 - 2015.
Mineral processing, Mt. Pass	USA	214	t Nd_2O_3	own calculation	Total AUS concentrate, 2015	AUS	8074	t REO			own calculation		Data values from 2013 - 2015.
SUM		29399	t Nd_2O_3	own calculation	Share Nd2O3 AUS, Mt. Weld	AUS	18.5	%			(Jaireth and Hoatson, 2014)		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					Quantity Concentrate AUS Nd2O3 per annum	AUS	1493.69	t Nd_2O_3			Own calculation		
					Quantity Concentrate CN Nd2O3, 2015	China	19938	t Nd_2O_3			Own calculation		
					Quantity Concentrate USA Nd2O3, 2015	USA	197	t Nd_2O_3			Own calculation		
					Metallurgical extracting Malaysia (LAMP) for Monazite by Rhône-Poulenc	AUS, Mt. Weld	90	%			Talens Peiró, 2013, p. 1338	Note: not used for calculation, since the concentrate mass was found in literature. This remains here for data completeness.	
					Metallurgical extracting Bayan Obo mineral for China	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	72	%			Talens Peiró, 2013, p. 1338		
					Metallurgical extracting USA with Kruesi and Duker process	USA, Mt Pass	92	%			Talens Peiró, 2013, p. 1338		
Mass fraction													

Indicator	**Location**	**Value**	**Unit**	**Reference**	**Sub-indicator**	**Location**	**Value**	**Unit**	**Value original**	**Unit**	**Reference**	**Remark**	**Assumption**
Mineral processing, Mt. Weld	Australia	19	% tNd_2O_3 / t material	(Jaireth and Hoatson, 2014)									
Mineral processing, Bayan Obo	China	17	% tNd_2O_3 / t material	(Zhi Li, 2014, Machacek 2015)									
Mineral processing, Mt. Pass	USA	12	% tNd_2O_3 / t material	(Habib, 2014)							(Habib, 2014, p. 357)		
Eligibility													
Market concentration													
Mineral processing, Mt. Weld	Australia	65	-	Own calculation	Mining amount REO	Mt. Weld, resp. Australia to world	10000	t			USGS, 2016, p. 135	Explanation: formulisation Σ (a2), e.g. with one supplier --> a market share from 100%: (1x100^2) = 10'000	
Mineral processing, Bayan Obo	China	7170	-	Own calculation	Mining amount	China to world	105000	t			USGS, 2016, p. 135		Data value includes entire China.
Mineral processing, Mt. Pass	USA	11	-	Own calculation	Mining amount	USA to world	4100	t			USGS, 2016, p. 135		Note, this value does not take into account the 40% illegal smuggling rate from China (Machacek et al. 2015)
					Mining amount	World total (rounded)	124000	t		USGS, 2016, p. 135	Quality control: value compared with Nasser, 2015 and are in a similar range.		
					Mining Shrare	Mt. Weld. To world total	8.1	%		own calculation			

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						China to world	84.7	%		own calculation			
						USA to world	3.3	%		own calculation			
Operating license													
Mineral processing, Mt. Weld	Australia	1	-	(Schmidt, 2013)							(Schmidt, 2013)	1' means existing operating license, whereas '0' non-existing operating license.	Data values range from 2013 - 2014.
Mineral processing, Bayan Obo	China	1	-	(Wübbeke, 2013)							(Wübbeke, 2013)		Data values range from 2013 - 2014.
Mineral processing, Mt. Pass	USA	1	-	(Machacek and Fold, 2014)							(Machacek and Fold, 2014)		Data values range from 2013 - 2014.
Technology													
Knowledge of machine and infrastructure													
Mineral processing, Mt. Weld	Australia	3	-	(Schmidt, 2013)							(Schmidt, 2013)	Quantify: weather knowledge does not exists (0), is in research (1) or scale up-phase (2) or large scale production (3).	Data values range from 2013 - 2014.
Mineral processing, Bayan Obo	China	3	-	(Wübbeke, 2013)							(Wübbeke, 2013)		Data values range from 2013 - 2014.
Mineral processing, Mt. Pass	USA	3	-	(Machacek and Fold, 2014)							(Machacek and Fold, 2014)		Data values range from 2013 - 2014.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Indexed annual rate of collection, mining recovery and processing recovery													
Mineral processing, Mt. Weld	Malaysia, LAMP Processing plant	76	%	Own calculation	Recovery rate mineral processing (beneficiation)	AUS, Mt. Weld	75	%			Talens Peiró, 2013, p. 1338		Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Mineral processing, Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	51	%	Own calculation	Recovery rate mineral processing (beneficiation)	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	50	%			Talens Peiró, 2013, p. 1338	'technology yield' (highest value if range given), for calculating a country difference. Generally, a higher value for the innovation index means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with the corresponding 'technology yield' value. This is called the 'share of innovation from technology'. To represent a more	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												innovative country (assumption: innovation aims for higher yield), from the 'technology yield' value, the 'share of innovation from technology' is then added. Attention, if the innovation index is negative, the 'share of innovation from technology' is subtarget to represent a country that is less innovative, since such a country is less likely to prioritise a higher yield.	
Mineral processing, Mt. Pass	USA, Mt Pass	92	%	Own calculation	Recovery rate mineral processing (beneficiation)	USA, Mt Pass	90	%			Talens Peiró, 2013, p. 1338	'technology yield' (highest value if range given), for calculating a country difference. Generally, a higher value for the innovation index means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												the corresponding 'technology yield' value. This is called the 'share of innovation from technology'. To represent a more innovative country (assumption: innovation aims for higher yield), from the 'technology yield' value, the 'share of innovation from technology' is then added. Attention, if the innovation index is negative, the 'share of innovation from technology' is subtarget to represent a country that is less innovative, since such a country is less likely to prioritise a higher yield.	
					Innovation Efficiency Ratio --> how much innovation is given for its inputs	Malaysia, LAMP Processing plant	1.014	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);		Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
						China Bastnäsite from Baotou and ion ad-	1.014	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						soption clay from Southern provinces							
						USA, Mt Pass	1.018	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);		
Economy													
Indexed costs in a country													
Mineral processing, Mt. Weld	Australia	1.23	$/kg REO, 45%	Own calculation	Costs Ce-oxide 45%		0.98	$/kg			metal pages, 2016 Prices accessible from price charts to non-subscribed users of metal-pages, Sep 2016.	Buchholz, 2014, 18 (DERA: Angebotskonzentration bei mineralischen Rohstoffen und Zwischenprodukten) uses Cer-compunds for other organic compounds of RE-metals. Consequently, we also used this compound as a representative for NdO, since at the market only this solid is handled.	Data sources from 2014 and 2016.
Mineral processing, Bayan Obo	China	0.65	$/kg REO, 45%	Own calculation	Labour costs	Australia	1.001	decimal	100.1	%	Trading Economics, 2016		Data sources from 2014 and 2016.
Mineral processing, Mt. Pass	USA	1.20	$/kg REO, 45%	Own calculation	China	1.036	decimal	103.6	%	Trading Economics, 2016	Data sources from 2014 and 2016.		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						USA	1.101	decimal	110.1	%	Trading Economics, 2016		
					Price level	Australia	1.25	decimal	125	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						China	0.64	decimal	64	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						USA	1.11	decimal	111	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
Indexed cost volatility in a country													
Mineral processing, Mt. Weld	Australia	N/A	N/A	N/A	Price level	World	0.98	$/kg				metal pages, 2016 Prices accessible from price charts to non-subscribed users of metal-pages, Sep 2016.	Buchholz, 2014, 18 (DERA: Angebotskonzentration bei mineralischen Rohstoffen und Zwischenprodukten) uses Cer-compunds for other organic compounds of RE-metals. Consequently, we also used this compound as a representative for Nd_2O_3, since at the market only this soild is handled.
Mineral processing, Bayan Obo	China	N/A	N/A	N/A		N/A							
Mineral processing, Mt. Pass	USA	N/A	N/A	N/A	Labour costs	Australia	1.001	decimal	100.1	%	Trading Economics, 2016		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						China	1.036	decimal	103.6	%	Trading Economics, 2016		
						USA	1.101	decimal	110.1	%	Trading Economics, 2016		
					Price level	Australia	1.25	decimal	125	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						China	0.64	decimal	64	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						USA	1.11	decimal	111	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
Society													
Working Conditions													
Human rights implications													
Freedom of speech													
Mineral processing, Mt. Weld	Australia	93	%	(World Bank, 2016)								Indicator: WGI: Voice and Accountability (VA), 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Mineral processing, Bayan Obo	China	5	%	(World Bank, 2016)									
Mineral processing, Mt. Pass	USA	81	%	(World Bank, 2016)									

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Societal stability													
Political stability													
Mineral processing, Mt. Weld	Australia	77	%	(World Bank, 2016)								Indicator: WGI: political stability and absence of violence/terrorism, 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Mineral processing, Bayan Obo	China	27	%	(World Bank, 2016)									
Mineral processing, Mt. Pass	USA	70	%	(World Bank, 2016)									
Environment													
Environmental regulatory requirement													
Environmental regulations and standards													
Mineral processing, Mt. Weld	Australia	1	-	(Lynas, 2016)								1' means existing environmental regulations and standards, such as ISO 14001, whereas '0' non-existing environ-	Data sources range from 1998 - 2016.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												mental regulations and standards.	
Mineral processing, Bayan Obo	China	0	-	-								Online search resulted in no confirmation, consequently it is assumed Bayan Obo is not certified, as in the certification it is stated that the certificate needs to be accessibly by the public	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.
Mineral processing, Mt. Pass	USA	1	-	(Chevron, 1998)									Data sources range from 1998 - 2016.
Total environmental impacts													
ReCiPe: Ecosystem and Human health													
Mineral processing, Mt. Weld	Australia	N/A	-	-									
Mineral processing, Bayan Obo	China	0.338	Pt	(Wolfensberger, 2015)								Value accounts also for mining	Data value accounts also for mining.
Mineral processing, Mt. Pass	USA	N/A	-	-									
Metallurgical Extraction													
Geological knowledge													

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Quantity													
Metallurgical extraction, Mt. Weld and Malaysia	Malaysia	644	t Nd_2O_3	own calculation	Quantity Refining Nd2O3, 2015	AUS	580	t Nd_2O_3			own calculation	Processing in LAMP plant Malaysia, Lynas	Data values from 2013 - 2015.
Metallurgical extraction, Bayan Obo	China	19938	t Nd_2O_3	own calculation	Quantity Refining Nd2O3, 2015	China	17944	t Nd_2O_3			own calculation	at present, 25.07.2016	Data values from 2013 - 2015.
Metallurgical extraction, Mt. Pass	USA	197	t Nd_2O_3	own calculation	Quantity Refining Nd2O3, 2015 production data available only first quarter	USA	177	t Nd_2O_3			own calculation	required	Data values from 2013 - 2015.
					Recovery rate from Refining	process specific	90	%			Talens Peiró, 2013, p. 1338		
Mass fraction													
Metallurgical extraction, Mt. Weld and Malaysia	Malaysia	85	% tREO / t material	(Simoni, 2015)									Value for REO used as an indication for Nd.
Metallurgical extraction, Bayan Obo	China	85	% tREO / t material	(Simoni, 2015)									Value for REO used as an indication for Nd.
Metallurgical extraction, Mt. Pass	USA	85	% tREO / t material	(Simoni, 2015)									Value for REO used as an indication for Nd.
Eligibility													

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Market concentration													
Metallurgical extraction, Mt. Weld and Malaysia	Malaysia	67.7	-	Own calculation	Mining amount REO	Mt. Weld and Malaysia to world	10200	t			USGS, 2016, p. 135	Explanation: formulisation Σ (a2), e.g. with one supplier --> a market share from 100%: (1x100^2) = 10'000	
Metallurgical extraction, Bayan Obo	China	7170.3	-	Own calculation	Mining amount	China to world	105000	t			USGS, 2016, p. 135		Data value includes entire China.
Metallurgical extraction, Mt. Pass	USA	10.9	-	Own calculation	Mining amount	USA to world	4100	t			USGS, 2016, p. 135		Note, this value does not take into account the 40% illegal smuggling rate from China (Machacek et al. 2015)
					Mining amount	World total (rounded)	124000	t			USGS, 2016, p. 135		
					Mining Shrare	Mt. Weld. To world total	8.2	%			own calculation		
						China to world	84.7	%			own calculation		
						USA to world	3.3	%			own calculation		
Operating license													
Metallurgical extracting, Mt. Weld	Malaysia	1	-	(Schmidt, 2013)							(Schmidt, 2013)	1' means existing operating license, whereas '0' non-existing operating license.	Data values range from 2013 - 2014.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Metallurgical extracting Bayan Obo	China	1	-	(Wübbeke, 2013)							(Wübbeke, 2013)		Data values range from 2013 - 2014.
Metallurgical extracting Mt. Pass	USA	1	-	(Machacek and Fold, 2014)							(Machacek and Fold, 2014)		Data values range from 2013 - 2014.
Technology													
Knowledge of machine and infrastructure													
Metallurgical extracting, Mt. Weld	Malaysia	3	-	(Schmidt, 2013)							(Schmidt, 2013)	Quantify: weather knowledge does not exists (0), is in research (1) or scale up-phase (2) or large scale production (3).	Data values range from 2013 - 2014.
Metallurgical extracting Bayan Obo	China	3	-	(Wübbeke, 2013)							(Wübbeke, 2013)		Data values range from 2013 - 2014.
Metallurgical extracting Mt. Pass	USA	3	-	(Machacek and Fold, 2014)							(Machacek and Fold, 2014)		Data values range from 2013 - 2014.
Indexed annual rate of collection, mining recovery and processing recovery													
Metallurgical extracting, Mt. Weld	Malaysia	91	%	Own calculation	Metallurgical extracting Malaysia (LAMP) for Monazite by		90	%			Talens Peiró, 2013, p. 1338	only used for geological mining 'technology yield' (highest value if range given), for calculating a coun-	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5%

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					Rhône-Poulenc							try difference. Generally, a higher value for the innovation index means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with the corresponding 'technology yield' value. This is called the 'share of innovation from technology'. To represent a more innovative country (assumption: innovation aims for higher yield), from the 'technology yield' value, the 'share of innovation from technology' is then added. Attention, if the innovation index is negative, the 'share of innovation from technology' is subtargeted to represent a country that is less innovative, since such a	to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												country is less likely to prioritise a higher yield.	
Metallurgical extracting Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	73	%	Own calculation	Metallurgical extracting Bayan Obo mineral for China		72	%			Talens Peiró, 2013, p. 1338	'technology yield' (highest value if range given), for calculating a country difference. Generally, a higher value for the innovation index means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with the corresponding 'technology yield' value. This is called the 'share of innovation from technology'. To represent a more innovative country (assumption: innovation aims for higher yield), from the 'technology yield' value, the 'share of innovation from technology' is then added. Attention, if the innovation index is negative,	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												the 'share of innovation from technology' is subtargeted to represent a country that is less innovative, since such a country is less likely to prioritise a higher yield.	
Metallurgical extracting Mt. Pass	USA, Mt Pass	93	%	Own calculation	Metallurgical extracting USA with Kruesi and Duker process		92	%			Talens Peiró, 2013, p. 1338	only used for geological mining 'technology yield' (highest value if range given), for calculating a country difference. Generally, a higher value for the innovation index means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with the corresponding 'technology yield' value. This is called the 'share of innovation from technology'. To represent a more innovative country (assumption: innovation aims for	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												higher yield), from the ‘technology yield’ value, the ‘share of innovation from technology’ is then added. Attention, if the innovation index is negative, the 'share of innovation from technology’ is subtargeted to represent a country that is less innovative, since such a country is less likely to prioritise a higher yield.	
					Innovation Efficiency Ratio --> how much innovation is given for it's inputs	Malaysia, LAMP Processing plant	1.014	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);	Since this process is well established, we assumed very similar conditions for the processing of magnets	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
						China Bastnäsite from Baotou and ion adsorption clay from Southern provinces	1.014	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);		
						USA, Mt Pass	1.018	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Economy													
Indexed costs in a country													
Metallurgical extracting, Mt. Weld	Malaysia	0.87	$/kg REO, 20-70%	Own calculation	Bastnäsite concentrate REO with Nd2O3 ~70-85% costs	world-wide	5.73	$/kg			USGS 2013, Mineral Commodity Summary; Simoni, 2015	Prices from 2009 used. The prices do not show any spike, due to the crisis.	Data sources from 2013 to 2016. Since 2015 is after the REE crisis, values from 2009 (before the crisis) were used.
Metallurgical extracting Bayan Obo	China	2.02	$/kg REO, 20-70%	Own calculation	Monazite concentrate REO with Nd2O3 ~70-85% costs	world-wide	0.87	$/kg			USGS 2013, Mineral Commodity Summary; Simoni, 2015	Prices from 2009 used. The prices do not show any spike, due to the crisis.	Data sources from 2013 to 2016. Since 2015 is after the REE crisis, values from 2009 (before the crisis) were used.
Metallurgical extracting Mt. Pass	USA	6.36	$/kg REO, 20-70%	Own calculation	Labour costs	Australia	0.91175	decimal	91.2	%	Trading Economics, 2017	Data from 2009	Data sources from 2013 to 2016. Since 2015 is after the REE crisis, values from 2009 (before the crisis) were used.
						China	1.035	decimal	103.5	%	Trading Economics, 2017		Data from Dec. 2016, value from 2009 not available
						USA	1.000043	decimal	100.0	%	Trading Economics, 2017	Data from 2009	
					Price level	Australia	1.1	decimal	110	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						China	0.45	decimal	45	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm	100 = OECD, all other countries are a relative thereof	

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						USA	1.11	decimal	111	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
					China Bastnäsite with labour costs and price level	China	2.668748				Own calculation		
					China Monazite with labour costs and price level	China	0.405203				Own calculation		
					Share Bastnäsite from concentrate	China	50	%			Sprecher Inventroy, 2014, page C	Remaining material to 100% are iron oxide and carbonates.	
					Share Monazite from concentrate	China	20	%			Sprecher Inventroy, 2014, page C	Remaining material to 100% are iron oxide and carbonates.	
					Total share Bastäsite & Monazite		70	%			Own calculation		
					Out of 100% Bastnäsite		71.42857	%			Own calculation		
					Out of 100% Monazite		28.57143	%			Own calculation		
					Total out of 100 % Mixture		100	%			Own calculation		
Indexed cost volatility in a country													
Metallurgical extracting, Mt. Weld	Malaysia	143	%	Own calculation	Bastnäsite concentrate REO with Nd2O3	worldwide	5.73	$/kg			USGS 2013, Mineral Commodity Summary	Prices from 2009 used. The prices do not show any spike, due to the crisis.	Data sources from 2013 to 2017. Since 2015 is after the REE crisis, values from 2005 and

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					~70-85% costs								2009 (before the crisis) were used.
Metallurgical extracting Bayan Obo	China	125	%	Own calculation	Monazite concentrate REO with Nd2O3 ~70-85% costs	worldwide	0.87	$/kg			USGS 2013, Mineral Commodity Summary	Prices from 2009 used. The prices do not show any spike, due to the crisis.	Data sources from 2013 to 2017. Since 2015 is after the REE crisis, values from 2005 and 2009 (before the crisis) were used.
Metallurgical extracting Mt. Pass	USA	168	%	Own calculation	2005: Bastnäsite concentrate REO with Nd2O3 ~70-85% costs	worldwide	4.08	$/kg			USGS 2006, Mineral Commodity Summary	Prices from 2005 used. The prices do not show any spike, due to the crisis.	Data sources from 2013 to 2017. Since 2015 is after the REE crisis, values from 2005 and 2009 (before the crisis) were used.
					2005: Monazite concentrate REO with Nd2O3 ~70-85% costs	worldwide	0.73	$/kg			USGS 2006, Mineral Commodity Summary	Prices from 2009 used. The prices do not show any spike, due to the crisis.	Data sources from 2013 to 2017. Since 2015 is after the REE crisis, values from 2005 and 2009 (before the crisis) were used.
					2009 Labour costs	Australia	0.91175	decimal	91.2	%	Trading Economics, 2017	Data from 2009	
						China	1.035	decimal	103.5	%	Trading Economics, 2017		Data from Dec. 2016, value from 2009 not available (since data recording only started in 2012)
						USA	1.000043	decimal	100.0	%	Trading Economics, 2017	Data from 2009	
					2005 Labour costs	2005: AUS	0.8015	decimal	80.2	%	Trading Economics, 2017	Data from 2005	

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						2005: CN	1.097	decimal	109.7	%	Trading Economics, 2017		Data from Dec. 2012, value from 2009 not available, (since data recording only started in 2012)
						2005: USA	0.947208	decimal	94.7	%	Trading Economics, 2017	Data from 2009	
					2009 Price level	Australia	1.1	decimal	110	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm		
						China	0.45	decimal	45	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm	Data from 2009	
						USA	1.11	decimal	111	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm		
					2005: Price level	2005: AUS	1.04	decimal	104	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm	Data from 2005	
						2005: CN	0.34	decimal	34	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm	Data from 2005	
						2005: USA	0.98	decimal	98	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm	Data from 2005	
					2009 and 2016: China Bastnäsite	China	2.668748				Own calculation		
					2009 and 2016: China Monazite	China	0.405203				Own calculation		
					2009 and 2016: China Bastnäsite	China	2.137175				Own calculation		
					2009 and 2016: China Mona-	China	0.324493				Own calculation		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					zite								
					Share Bastnäsite from concentrate	China	50	%			Sprecher Inventroy, 2014, page C	Remaining material to 100% are iron oxide and carbonates.	
					Share Monazite	China	20	%			Sprecher Inventroy, 2014, page C	Remaining material to 100% are iron oxide and carbonates.	
					Total share Bastäsite & Monazite		70	%		Own calculation			
					Out of 100% Bastnäsite		71.42857	%		Own calculation			
					Out of 100% Monazite		28.57143	%		Own calculation			
					Total out of 100 % Mixture		100	%		Own calculation			
Society													
Working Conditions	**N/A**												
Human rights implications													
Freedom of speech													
Metallurgical extracting, Mt. Weld	Malaysia	36	%	(World Bank, 2016)								Indicator: WGI: Voice and Accountability (VA), 2015 data; Unit: Percentile rank among all countries (ranges from	

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												0 (lowest) to 100 (highest) rank)	
Metallurgical extracting Bayan Obo	China	5	%	(World Bank, 2016)									
Metallurgical extracting Mt. Pass	USA	81	%	(World Bank, 2016)									
Societal stability													
Political stability													
Metallurgical extracting, Mt. Weld	Malaysia	54	%	(World Bank, 2016)								Indicator: WGI: political stability and absence of violence/terrorism, 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Metallurgical extracting Bayan Obo	China	27	%	(World Bank, 2016)									
Metallurgical extracting Mt. Pass	USA	70	%	(World Bank, 2016)									
Environment													
Environmental regulatory requirement													

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Environmental regulations and standards													
Metallurgical extracting, Mt. Weld	Malaysia	1	-	(Lynas, 2016)								1' means existing environmental regulations and standards, such as ISO 14001, whereas '0' non-existing environmental regulations and standards.	Data sources range from 1998 - 2016.
Metallurgical extracting Bayan Obo	China	0	-	-								Online search resulted in no confirmation, consequently it is assumed Bayan Obo is not certified, as in the certification it is stated that the certificate needs to be accessibly by the public	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.
Metallurgical extracting Mt. Pass	USA	1	-	(Chevron, 1998)									Data sources range from 1998 - 2016.
Total environmental impacts													
ReCiPe: Ecosystem and Human health													
Metallurgical extracting, Mt. Weld	Malaysia	N/A	-	-									

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Metallurgical extracting Bayan Obo	China	2.659	Pt	(Wolfensberger, 2015)									Data value accounts also for refining.
Metallurgical extracting Mt. Pass	USA	N/A	-	-									
Refining													
Geological knowledge													
Quantity													
Refining, Mt. Weld	Malaysia	580	t Nd_2O_3	(Machacek, 2015, p. 85)	AUS first half REO, 2015		2050	t REO			(Lynas, 2015 Annual Report, p. 10)		Data values from 2014 - 2015.
Refining, Bayan Obo	China	17944	t Nd_2O_3	own calculation	AUS second half REO, 2015		1083	t REO			(Lynas, 2016 First Half Financial Report, p. 3, assuming that all bached and ready for production volume was produced into REO)		Data values from 2014 - 2015.
Refining, Mt. Pass, first quarter of 2015	USA	177	t Nd_2O_3	own calculation	AUS total REO 2015		3133	t REO			(Lynas, 2016 First Half Financial Report, p. 3, assuming that all bached and ready for production volume was produced into REO)		Data values from 2014 - 2015.
Refining total	total	18701	t Nd_2O_3	own calculation	Share Nd2O3 AUS, Mt. Weld		18.5	%			(Jaireth and Hoatson, 2014)		
					AUS Nd2O3, 2015		580	t Nd_2O_3			own calculation		
					China, 2015		17944	t Nd_2O_3			(Machacek, 2015, p. 85)		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
					USA first quarter REO, 2015		1479	t REO			(Molycorp, 2015)		
					Share Nd2O3		12	%			(Habib, 2014, p. 357)		
					USA first quarter Nd2O3, 2015		177	t Nd_2O_3			own calculation		
					Cross check resto of the world								
					AUS and USA		757	t Nd_2O_3				other large producing countries include Russia and Thailand with approx. Half as much as AUS. (USGS, 2016)	
					Rest of the world production ratio, 2015		14	%			(Machacek, 2015, p. 85)		
					Rest of the world, 2015		2921	t Nd_2O_3			(Machacek, 2015, p. 85)		
Verification of numbers													
Total Global Refining REO, 2013	global REO	90011	t REO	(Marscheider-Wiedemann, 2016, p. 274)									
Total Global Refining REO, 2010	global REO	121878	t REO	(Marscheider-Wiedemann, 2016, p. 274)									

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
	Share Nd2O3	15.4	%	(Machacek, 2015, p. 85)									
Total Global Refining Nd2O3, 2013	global Nd2O3	13862	t Nd_2O_3	own calculation									
Total Global Refining Nd2O3, 2010	global Nd2O3	18769	t Nd_2O_3	own calculation									
Conclusion: vslues are possible, especially since the share has increased slightly as stated in Simoni, 2015													
Mass fraction													
Refining, Mt. Weld	Malaysia	99.5	% tNd_2O_3 / t material	(USGS, 2016)									
Refining, Bayan Obo	China	99.5	% tNd_2O_3 / t material	(USGS, 2016)									
Refining, Mt. Pass	USA	99.5	% tNd_2O_3 / t material	(USGS, 2016)									
Eligibility													

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Market concentration													
Refining, Mt. Weld	Malaysia	67.7	-	Own calculation	Mining amount REO	Mt. Weld and Malaysia to world	10200	t			USGS, 2016, p. 135	Explanation: formulisation Σ (a2), e.g. with one supplier --> a market share from 100%: (1x100^2) = 10'000	
Refining, Bayan Obo	China	7170.3	-	Own calculation	Mining amount	China to world	105000	t			USGS, 2016, p. 135	Data value for entire China.	
Refining, Mt. Pass	USA	10.9	-	Own calculation	Mining amount	USA to world	4100	t			USGS, 2016, p. 135		Note, this value does not take into account the 40% illegal smuggling rate from China (Machacek et al. 2015)
					Mining amount	World total (rounded)	124000	t			USGS, 2016, p. 135		
					Mining Shrare	Mt. Weld. To world total	8.2	%			own calculation		
						China to world	84.7	%			own calculation		
						USA to world	3.3	%			own calculation		
Operating license													
Refining, Mt. Weld	Malaysia	1	-	(Schmidt, 2013)							(Schmidt, 2013)	1' means existing operating license, whereas '0' non-existing operating license.	Data values range from 2013 - 2014.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Refining, Bayan Obo	China	1	-	(Wübbeke, 2013)							(Wübbeke, 2013)		Data values range from 2013 - 2014.
Refining, Mt. Pass	USA	1	-	(Machacek and Fold, 2014)							(Machacek and Fold, 2014)		Data values range from 2013 - 2014.
Technology													
Knowledge of machine and infrastructure													
Refining, Mt. Weld	Malaysia	3	-	(Schmidt, 2013)							(Schmidt, 2013)	Quantify: weather knowledge does not exists (0), is in research (1) or scale up-phase (2) or large scale production (3).	Data values range from 2013 - 2014.
Refining, Bayan Obo	China	3	-	(Wübbeke, 2013)							(Wübbeke, 2013)		Data values range from 2013 - 2014.
Refining, Mt. Pass	USA	3	-	(Machacek and Fold, 2014)							(Machacek and Fold, 2014)		Data values range from 2013 - 2014.
Indexed annual rate of collection, mining recovery and processing recovery													
Refining, Mt. Weld	Malaysia	91	%	Own calculation	Solvent extraction, precipitation	Precipitation and multiple solvent extraction	90	%			Talens Peiró, 2013, p. 1338	'technology yield' (highest value if range given), for calculating a country difference. Generally, a higher value for the innovation index	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with the corresponding 'technology yield' value. This is called the 'share of innovation from technology'. To represent a more innovative country (assumption: innovation aims for higher yield), from the 'technology yield' value, the 'share of innovation from technology' is then added. Attention, if the innovation index is negative, the 'share of innovation from technology' is subtargeted to represent a country that is less innovative, since such a country is less likely to prioritise a higher yield.	

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Refining, Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	91	%	Own calculation	Innovation Efficiency Ratio --> how much innovation is given for it's inputs	Malaysia, LAMP Processing plant	1.014	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);	‘technology yield’ (highest value if range given), for calculating a country difference. Generally, a higher value for the innovation index means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with the corresponding ‘technology yield’ value. This is called the ‘share of innovation from technology’. To represent a more innovative country (assumption: innovation aims for higher yield), from the ‘technology yield’ value, the ‘share of innovation from technology’ is then added. Attention, if the innovation index is negative, the 'share of innovation from technology’ is sub-	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												targeted to represent a country that is less innovative, since such a country is less likely to prioritise a higher yield.	
Refining, Mt. Pass	USA, Mt Pass	91	%	Own calculation	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces		1.014	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);	'technology yield' (highest value if range given), for calculating a country difference. Generally, a higher value for the innovation index means a higher technological invention. This can be used as a country differentiation. For this, our estimated share of innovation [Our weighting of the innovation index is divided by 100] is multiplied with the corresponding 'technology yield' value. This is called the 'share of innovation from technology'. To represent a more innovative country (assumption: innovation aims for higher yield), from the 'technology yield' value, the 'share of innovation from technol-	Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
												ogy' is then added. Attention, if the innovation index is negative, the 'share of innovation from technology' is subtargeted to represent a country that is less innovative, since such a country is less likely to prioritise a higher yield.	
						USA, Mt Pass	1.018	-			INSEAD, 2015 & own weighting with yield for REE range 20 from 50 - 70% Althaus, 2007 --> arithmetic mean value is 0 (with $^{+}$/- 10%);		Data values from 2013 and 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Economy													
Indexed costs in a country													
Refining, Mt. Weld	Malaysia	46	$/kg Nd2O3	Own calculation	Nd Oxide 99.5& minimum	world	37	$/kg			USGS, 2016, Rare Earth data set		
Refining, Bayan Obo	China	24	$/kg Nd2O4	Own calculation	Labour costs	Australia	1.001	decimal	100.1	%	Trading Economics, 2016		
Refining, Mt. Pass	USA	46	$/kg Nd2O5	Own calculation		China	1.036	decimal	103.6	%	Trading Economics, 2016		
						USA	1.101	decimal	110.1	%	Trading Economics, 2016		
					Price level	Australia	1.24	decimal	124	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						China	0.63	decimal	63	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						USA	1.13	decimal	113	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
Indexed cost volatility in a country													
Refining, Mt. Weld	Malaysia	16	%	Own calculation	2015 Nd Oxide 99.5% min.	world	37	$/kg			USGS, 2016, Rare Earth data set		Data values from 2011 and 2015.
Refining, Bayan Obo	China	22	%	Own calculation	2011 Nd Oxide 99.5% min.	world	190	$/kg			USGS, 2016, Rare Earth data set		Data values from 2011 and 2015. Labour costs value was only available from 2012.
Refining, Mt. Pass	USA	25	%	Own calculation	2015 Labour costs	Australia	1.001	decimal	100.1	%	Trading Economics, 2016		Data values from 2011 and 2015.
						China	1.036	decimal	103.6	%	Trading Economics, 2016		
						USA	1.101	decimal	110.1	%	Trading Economics, 2016		
					2011 Labour costs	Australia	0.99575	decimal	99.575	%	Trading Economics, 2016		
						China	1.097	decimal	109.7	%	Trading Economics, 2016		Data from Dec. 2012, value from 2011 not available, (since data recording only started in 2012)
						USA	1.00724	decimal	100.724	%	Trading Economics, 2016		
					2015 Price level	Australia	1.24	decimal	124	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
						China	0.63	decimal	63	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						USA	1.13	decimal	113	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
					2011 Price level	Australia	1.48	decimal	148	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						China	0.52	decimal	52	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
						USA	0.95	decimal	95	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
Society													
Working Conditions	**N/A**												
Human rights implications													
Freedom of speech													
Refining, Mt. Weld	Malaysia	36	%	(World Bank, 2016)								Indicator: WGI: Voice and Accountability (VA), 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Refining, Bayan Obo	China	5	%	(World Bank, 2016)									
Refining, Mt. Pass	USA	81	%	(World Bank, 2016)									

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Societal stability													
Political stability													
Refining, Mt. Weld	Malaysia	54	%	(World Bank, 2016)								Indicator: WGI: political stability and absence of violence/terrorism, 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Refining, Bayan Obo	China	27	%	(World Bank, 2016)									
Refining, Mt. Pass	USA	70	%	(World Bank, 2016)									
Environment													
Environmental regulatory requirement													
Environmental regulations and standards													
Refining, Mt. Weld	Malaysia	1	-	(Lynas, 2016)								1' means existing operating license, whereas '0' non-existing operating license.	Data sources range from 1998 - 2016.

Indicator	Location	Value	Unit	Reference	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumption
Refining, Bayan Obo	China	0	-	-								Online search resulted in no confirmation, consequently it is assumed Bayan Obo is not certified, as in the certification it is stated that the certificate needs to be accessibly by the public	Data sources range from 1998 - 2016. No information online available, thus assumed to have no certification for environmental standards.
Refining, Mt. Pass	USA	1	-	(Chevron, 1998)									Data sources range from 1998 - 2016.
Total environmental impacts													
ReCiPe: Ecosystem and Human health													
Refining, Mt. Weld	Malaysia	N/A	-	-									
Refining, Bayan Obo	China	2.659	Pt	(Wolfensberger, 2015)								Value accounts also for metallurgical extraction	Data value accounts also for metallurgical extracting.
Refining, Mt. Pass	USA	N/A	-	-									

G.8 Framework application, results and discussion: detailed quantification of mining deposits in the anthroposphere

Figure 30 Results from quantifying MDA (mining deposits in the anthroposphere) for Nd_2O_3 from HDD along the operational steps. Note: the masses are always output masses of one process and are here equivalent to the input passes of the next process.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Collection														
Geological knowledge														
Annual mass flow														
Collection, Desktop-PC	Switzerland	1.229	t Nd	own calculation		PC servers collected 2015	Switzerland	5320	ton	402000	unit			
Quantity Collection, Laptop	Switzerland	0.409	t Nd	own calculation		Laptop collected 2015		1214	ton	410000	unit			
Collecting, Switzerland	Switzerland	1.637	t Nd	own calculation		Average PC servers collected 2015, weight		13233.8	g PC, server / 1 unit PC, server					Data values partially from 2014 - 2015.
Collection, Desktop-PC	Switzerland	1.433	t Nd_2O_3	own calculation	Input value Switzerland	Average Laptop collected 2015, weight		2961.0	g laptop / 1 unit laptop			(Swico 2016, technical report)		Data from 2015
Quantity Collection, Laptop	Switzerland	0.477	t Nd_2O_3	own calculation		Share HDD in 1 PC		3.3	%	3.3	%	(Swico 2016, technical report)		Data from 2015
Collecting, Switzerland	Switzerland	1.910	t Nd_2O_3	own calculation		Weight all HDD PC servers, computers in CH		175,560	kg HDD	175,560.00	kg			Data values partially from 2014 - 2015.
						Weight all HDD PC laptops in CH		40,062	kg HDD				+/- 68 g	
						Weight HDD Collection,		542	g / 1 HDD	175,560,000.00	g / CH HDD	(Ueberschaar, 2015)		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Desktop-PC								
Verification						Weight HDD Collection, Laptop		134	g / 1 HDD	134	g / 1 HDD			
Collecting, total	Switzerland	1.637	t Nd	own calculation		Sprecher Weight $Nd_2Fe_{14}B$ / HDD Desktop		12.62	g $Nd_2Fe_{14}B$ / HDD	12.62	g $Nd_2Fe_{14}B$ / HDD			
Collecting, total Thébaud et al. 2017	Switzerland	2.835	**t Nd**	Thiébaud, et al. Where do do all the resources go, submitted.	Data include: ell electronic equipment of CH, not only HDD	Sprecher weight $Nd_2Fe_{14}B$ / HDD Laptop Sprecher		2.5	g $Nd_2Fe_{14}B$ / HDD	2.5	g $Nd_2Fe_{14}B$ / HDD	(Ueberschaar, 2015)	+/- 26 g	
Conclusion: less than half according to E. Thiébauds , material flow of Nd in all electric equip-equipment in CH. Consequently this seems to is possible, especially combined with the low data quality ranking.	Weight Empa Magnets from HDD Desktop	72	g $Nd_2Fe_{14}B$ / HDD	72	g $Nd_2Fe_{14}B$ / HDD							(Ueberschaar, 2015)		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Weight Empa Magnets from HDD Laptop		19.9	g $Nd_2Fe_{14}B$ / HDD	19.9	g $Nd_2Fe_{14}B$ / HDD	(Sprecher et al. 2014)		
						Empa Number of dismantled HDD Desktop		7	No	7	No	(Sprecher et al. 2014)		
						Empa Number of dismantled HDD Laptop		4	No	4	No	(BAFU 2015, e-Recmet final report)		calculation based on 17.87 − 0.35 * t gram (t = 0@1990) and base year (t=0@1990); and 2015 (date of e-recmet study)
						Average weight Nd2Fe14B / HDD Desktop		11.45285714	g $Nd_2Fe_{14}B$ / HDD	11.45285714	g $Nd_2Fe_{14}B$ / HDD	(BAFU 2015, e-Recmet final report)		
						Average weight Nd2Fe14B / HDD Laptop		3.7375	g $Nd_2Fe_{14}B$ / HDD	3.7375	g $Nd_2Fe_{14}B$ / HDD	(BAFU 2015, e-Recmet final report)		
						Molecular weight Nd		144.24	g/mol	144.24	g/mol	(BAFU 2015, e-Recmet final report)		
						Molecular weight Nd2O3		336.4822	g/mol	336.4822	g/mol	own calculation		
						Molecular weight Nd2Fe14B magnet		1081.125	g/mol	1081.125	g/mol	own calculation		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Percentage Nd in Nd2Fe14B		0.13341658	mol-%	0.13341658	mol-%	(Pubchem 2016)	range: 10.286g - 12.62g	
						Weight Nd2O3 from HDD Desktop		3.564511567	g Nd2O3 / HDD	3.564511567	g Nd2O3 / HDD	(Pubchem 2016)	range: 2.5g - 4.975g	
						Weight Nd2O3 from HDD Laptop		1.163234799	g Nd2O3 / HDD	1.163234799	g Nd2O3 / HDD	(Pubchem 2016)		
						Weight Nd2O3 from kg HDD Desktop		6.576589607	g Nd2O3 / kg HDD	0.000495748	g Nd2O3 / kg HDD			
						Weight HDD / kg Nd2O3 Desktop Sandra		152.05	kg HDD / kg Nd2O3	2,017,154.91	kg HDD / kg Nd2O3			
						Weight Nd2O3 from kg HDD Laptop		8.680856712	g Nd2O3 / kg HDD	8.680856712	g Nd2O3 / kg HDD			
						Weight HDD / kg Nd2O3 Laptop Sandra		**115.1960035**	kg HDD / kg Nd2O3	**115.1960035**	kg HDD / kg Nd2O3			
						Verification calculation with Rolf Widmer and Marcel Gauch								
						Weight Nd from HDD Desktop		3.056002061	g Nd / HDD	3.056002061	g Nd / HDD			

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Weight Nd from HDD Laptop		0.997288935	g Nd / HDD	0.997288935	g Nd / HDD			
						Mass fraction g Nd / kg HDD Desktop		5.638380187	g Nd / kg HDD	0.000425025	g Nd / kg HDD			
						Mass fraction g Nd / kg HDD Laptop		7.44245474	g Nd / kg HDD	7.44245474	g Nd / kg HDD			
						Share Nd2 in Nd2O3 general		1.166396977	g Nd2O3 / g Nd	1.166396977	g Nd2O3 / g Nd			
						Share Nd2 in Nd2O3 general		1.166396977	g Nd2O3 / g Nd	1.166396977	g Nd2O3 / g Nd			
						Share Nd2O3 in kg HDD Desktop		6.576589607	g Nd2O3 / kg HDD	0.000495748	g Nd2O3 / kg HDD			
						Share Nd2O3 in kg HDD Laptop		8.680856712	g Nd2O3 / kg HDD	8.680856712	g Nd2O3 / kg HDD			
Mass fraction														
Collected all recycler Desktop PC	Switzerland	0.02309235	% t Nd / t average Desktop PC in CH, 2015	own calculation		Collection, Desktop-PC	Switzerland	1.229	t Nd	own calculation				
Collected all recycler Laptop	Switzerland	0.03368109	% t Nd / t Laptop	own calculation		Quantity Collection, Laptop	Switzerland	0.409	t Nd	own calculation				
Collecting, Switzerland	**Switzerland**	**0.02505971**	**% t Nd / t Desktop PC and Laptop**	**own calculation**		**Collecting, Switzerland**	**Switzerland**	**1.637**	**t Nd**	**own calculation**				Same data sources as for mass calculation.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Collected all recycler Desktop PC	Switzerland	0.02693484	% t Nd_2O_3 / t Desktop PC	own calculation		Collection, Desktop-PC	Switzerland	1.433	t Nd_2O_3	own calculation				
Collected all recycler Laptop	Switzerland	0.03928552	% t Nd_2O_3 / t t Laptop	own calculation		Quantity Collection, Laptop	Switzerland	0.477	t Nd_2O_3	own calculation				
Collecting, Switzerland	**Switzerland**	**0.02922957**	**% t Nd_2O_3 / t Desktop PC and Laptop**	**own calculation**	Assuming a 1 / 1 share of laptops and desktop PC's	**Collecting, Switzerland**	**Switzerland**	**1.910**	**t Nd_2O_3**	**own calculation**				Same data sources as for mass calculation.
						Weight collected Desktop PC	Switzerland	5320	t			(Swico 2016, technical report)		
						Weight collected Laptop	Switzerland	1214	t			(Swico 2016, technical report)		
						Weight collected, total	Switzerland	6534.00	t	own calculation				
Eligibility														
Market concentration														
Collecting, Switzerland	Switzerland	0.01	-	(Swico Abgabestellen, 2017)	Collection points from Swico			600.00				(Swico Abgabestellen, 2017)		Data values from 2017.
						Collection points at specialist retailers				447.00		(Elekektronikmärkte Schweiz, 2017		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Total collection points				1047.00		own calculation		Assumption: the collection points at dismantlers and recyclers was neglected since they are <20
						Market share				0.10		own calculation		Assumed, equally since the recycling system organising unit (Swico) strongly organizes the recycling, thus there is no free market (Swico, 2013). Calculation: 1047 --> 100%; 1 operator (since equal share and all have the same chance of receiving material) --> x; x= 0.10
Operating license														
Collecting, Switzerland	Switzerland	1	-	(Böni, 2015)								(Böni, 2015)	1' means existing operating license, whereas '0' non-existing operating license.	Data value for entire Switzerland.
Technology														
Knowledge of machine and infrastruc-														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
ture														
Collecting, Switzerland	Switzerland	3	-	(Böni, 2015)								(Böni, 2015)	Quantify: weather knowledge does not exists (0), is in research (1) or scale up-phase (2) or large scale production (3).	Data value for entire Switzerland.
Indexed annual rate of collection, mining recovery and processing recovery														
Collecting, Switzerland	Switzerland	51	%	Own calculation		Recovery rate Collection Desktop-PC	Switzerland	50	%			Rademaker, 2013		Data values from 2013 to 2015 and innovation efficiency normalised data values to range between 0.5% to 2%.
						Innovation Efficiency Ratio --> how much innovation is given for it's inputs	Switzerland	1.02				INSEAD, 2015 & normalised values to range between 0.5% to 2%.		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Economy														
Indexed costs in a country														
Collecting, Switzerland	Switzerland	0.49	$ / kg HDD	Own calculation		Cost total	Switzerland	31,100,000	CHF / CH			Swico annual report, 2016	Data from 2015	Data sources range from 2015 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
						Cost share logistic	Switzerland	30	%			Swico annual report, 2016		Data from 2015
						Cost share collection place	Switzerland	19	%			Swico annual report, 2016		Data from 2015
						Cost for collection	Switzerland	15,239,000	CHF / CH collection and collection place			Own calculation		
						Mass of PC/ Server and Laptop	Switzerland	6534	t			(Swico 2016, technical report)		
						Mass total IT		54721	t			(Swico 2016, technical report)		
						Share PC/Server		11.94	%			Own calculation		Data from 2015
						Cost for collection PC/server	1,819,624	CHF / all PC, server and lap-				Own calculation		Data from 2015

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						and laptop		top						
						Cost for collection PC/server and laptop	0.278	CHF / kg PC, server and laptop				Own calculation		
						Conversion factor, CHF to USD	1.01884					XE, 2016 conversion calculator		
						Labour costs	Norway to represent Switzerland	1.187	decimal	118.7	%	Trading Economics, 2016		
						Price level		1.46	decimal	146	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		
Indexed cost volatility in a country														
Collecting, Switzerland	Switzerland	110	%	Own calculation		Cost total	Switzerland	31,100,000	CHF / CH			Swico annual report, 2016	Since rough calculation, same data assumed for 2011	Data sources range from 2011 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
						Cost share logistic	Switzerland	30	%			Swico annual report, 2016	Since rough calculation,	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
													same data assumed for 2011	
						Cost share collection place	Switzerland	19	%			Swico annual report, 2016	Since rough calculation, same data assumed for 2011	
						Cost for collection	Switzerland	15,239,000	CHF / CH collection and collection place			Own calculation		
						Share of IT collection	Switzerland							
						Cost of collection of IT	Switzerland							
						Mass of PC/ Server and Laptop	Switzerland	147.9775	t			(Swico 2016, technical report)		Since rough calculation, same data assumed for 2011
						Mass total IT		54721	t			(Swico 2016, technical report)		Since rough calculation, same data assumed for 2011
						Share PC/Server		0.27	%			Own calculation		
						Cost for collection PC/server and laptop	41,210	CHF / all PC, server and laptop						
						Cost for collection PC/server and laptop	0.278	CHF / kg PC, server and laptop				Own calculation		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Conversion factor, CHF to USD	1.01884					XE, 2016 conversion calculator		
						2015: Labour costs	Switzerland	1.19	decimal	118.7	%	Trading Economics, 2016	Norway instead of Switzerland	
						2011: Labour costs	Switzerland	1.05	decimal	105.25	%	Trading Economics, 2016	Norway instead of Switzerland	
						2015: Price level	Switzerland	1.46	decimal	146	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm		
						2011: Price level	Switzerland	1.50	decimal	150	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm		
Society														
Human rights implications														
Freedom of speech														
Collecting, Switzerland	Switzerland	99.01	%	(World Bank, 2016)									Indicator: WGI: Voice and Accountability	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
													(VA), 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Political stability														
Political stability														
Collecting, Switzerland	Switzerland	95.2	%	(World Bank, 2016)									Indicator: WGI: political stability and absence of violence/terrorism, 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Environment														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Environmental regulatory quirement														
Environmental regulations and standards														
Collecting, Switzerland	Switzerland	1	-	(Cenelec 50625-2, 2015)									1' means existing environmental regulations and standards, such as ISO 14001, whereas '0' non-existing environmental regulations and standards.	
Total environmental impacts														
ReCiPe: Ecosystem and Human health														
Collecting, Switzerland	Switzerland	0.00112949	Pt	(Wolfensberger, 2015)										

Indicator	**Location**	**Value**	**Unit**	**Reference**	**Comment**	**Sub-indicator**	**Location**	**Value**	**Unit**	**Value original**	**Unit**	**Reference**	**Remark**	**Assumptions**
Manual and mechanical processing														
Geological knowledge														
Annual mass flow														
Manual processing, Switzerland	**Switzerland**	**1.47**	t Nd	**own calculation**		**Collecting, Switzerland**	**Switzerland**	**1.637**	**t Nd**			**own calculation**		Data values partially from 2014 - 2015.
Mechanical processing, Switzerland	**Switzerland**	**0.16**	t Nd	**own calculation**		Collection Nd2O3 Desktop Sandra	1.433	t Nd_2O_3			own calculation			Data values partially from 2014 - 2015.
Manual processed magnets, Desktop-PC	Switzerland	1.29	t Nd_2O_3	own calculation		Collection Nd2O3 Laptop Sandra	0	t Nd_2O_3			own calculation			
Manual processed magnets, Laptops	Switzerland	0.43	t Nd_2O_3	own calculation		Recovery rate Manual processing	Switzerland	90	%		(Sprecher, 2014)			
Mechanical processing HDD Desktop-PC	Switzerland	0.14	t Nd_2O_3	own calculation		Recovery rate Manual processing	10	%			(Sprecher, 2014)			
Mechanical processing HDD Laptop	Switzerland	0.05	t Nd_2O_3	own calculation										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Manual processing, Switzerland	**Switzerland**	**1.72**	t Nd_2O_3	own calculation										Data values partially from 2014 - 2015.
Mechanical processing, Switzerland	**Switzerland**	**0.19**	t Nd_2O_3	own calculation										Data values partially from 2014 - 2015.
Verification						**Verification**								
Manual processing, Switzerland	**Switzerland**	**1.72**	t Nd_2O_3	own calculation		Weight kg Nd2O3 Desktop Sandra	**1.43**	t Nd_2O_3				own calculation		
Mechanical processing, Switzerland	**Switzerland**	**0.19**	t Nd_2O_3	own calculation		Weight kg Nd2O3 Laptop Sandra	0.48	t Nd_2O_3				own calculation		
						Weight kg Nd2O3 total Sandra		**1.91**	t Nd_2O_3			own calculation		
Mass fraction														
Manual processing and mechanical processing, Switzerland	Switzerland	27	% tNd / t Nd2Fe14B magnet	own calculation		Molecular weight Nd		144.24	g/mol	144.24	g/mol	(Pubchem 2016)		
Manual processing	Switzerland	31.1	% tNd_2O_3 / t Nd2Fe14B	own calculation	Molecular weight 2(Nd)			288.48	g/mol	144.24	g/mol	(Pubchem 2016)		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
and mechanical processing, Switzerland			magnet											
						Molecular weight Nd2O3		336.4822	g/mol	336.4822	g/mol	(Pubchem 2016)		
						Molecular weight Nd2Fe14B magnet		1081.125	g/mol	1081.125	g/mol	(Pubchem 2016)		
Eligibility														
Market concentration														
Manual processing and mechanical processing, Switzerland	Switzerland	83	-	(Swico, 2017)		Number of authorised companies in Switzerland	11	no				(Swico, 2017)		Data from 2013 and 2017 and assumed since dismantlers are employed by the recyclers and in the material flow assessment they are integrated in the recyclers, for the HHI, they were also integrated in the recyclers and not differentiated separately. Marked share is assumed to be equally, since the SWICO recycling system is planning the recycling, consequently there is no free market (Swico, 2013).

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Market share		9.090909091	%			(Swico, 2013)		Assumed, equally since the recycling system organising unit (Swico) strongly organizes the recycling, thus there is no free market (Swico, 2013). Calculation: 11 --> 100%; 1 operator (since equal share and all have the same chance of receiving material) --> x; x=9.09
Operating license														
Manual processing and mechanical processing, Switzerland	Switzerland	1	-	(Böni, 2015)								(Böni, 2015)	1' means existing operating license, whereas '0' non-existing operating license.	Data value for entire Switzerland.
Technology														
Knowledge of machine and infrastructure														
Manual processing and mechanical processing,	Switzerland	1	-	(Böni, 2015)								(Böni, 2015)	Quantify: weather knowledge does not exists (0), is in research (1)	Data value for entire Switzerland.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Switzerland													or scale up-phase (2) or large scale production (3).	
Indexed annual rate of collection, mining recovery and processing recovery														
Manual processing	Switzerland	91.8	%	Own calculation		Recovery rate Manual processing	Switzerland	90	%			(Sprecher, 2014)		Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Mechanical processing	Switzerland	10.2	%	Own calculation	Recovery rate Mechanical processing	Switzerland	10	%				(Sprecher, 2014)		Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
						Innovation Efficiency Ratio --> how much innovation is given for it's inputs	Switzerland	1.020	-			INSEAD, 2015 & normalised values to range between 0.5% to 2%		
Economy														
Indexed costs in a country														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Manual processing and mechanical processing, costs	Switzerland	84	Costs aggregated $ / kg magnets	Own calculation	**Manual processing**									Data sources range from 2015 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
Mechanical processing costs	Switzerland	0.1	Costs aggregated $ / kg magnets	Own calculation		Desktop-PC manual processing costs	Switzerland	9.9	CHF/ **HDD to magmets**			(BAFU 2015, e-Recmet final report)		Data sources range from 2015 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
						Laptop manual processing costs	Switzerland	10.3	CHF/ **HDD to magmets**			(BAFU 2015, e-Recmet final report)		
						Weight HDD, Desktop-PC		542	g / 1 HDD			(Ueberschaar, 2015)		
						Weight HDD , Laptop		134	g / 1 HDD			(Ueberschaar, 2015)		
						Unit of HDD Desktop		402000	unit					
						Unit of HDD Laptop		410000	unit					

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Average weight Nd2Fe14B / HDD Desktop		11.45285714	g $Nd_2Fe_{14}B$ / HDD	11.45285714	g $Nd_2Fe_{14}B$ / HDD	own calculation	range: 10.286g - 12.62g	
						Average weight Nd2Fe14B / HDD Laptop		3.7375	g $Nd_2Fe_{14}B$ / HDD	3.7375	g $Nd_2Fe_{14}B$ / HDD	own calculation	range: 2.5g - 4.975g	
						Desktop-PC costs per magnets		0.2092	CHF/ magnets, PC in 1 HDD					
						Laptop costs per magnets		0.2873	CHF/ magnets, Laptop in 1 HDD					
						Desktop-PC costs per magnets in Switzerland	Switzerland	84096	CHF/ magnets, PC in Switzerland					
						Laptop costs per magnets in Switzerland	Switzerland	117787	CHF/ magnets, Laptop in Switzerland					
						Share Desktop in Switzerland		0.495	share					
						Share Laptop in Switzerland		0.505	share					
						Weight, Desktop-PC of all magnets in CH		4,604.05	kg Desktop-PC magnets in CH					

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Weight, Laptop of all magnets in CH		1,532.38	kg Laptop magnets in CH					
						Costs per kg PC-magnet, Switzerland for manual processing		18.27	CHF/ kg magnets, PC in Switzerland					
						Costs per kg Laptop-magnet, Switzerland for manual processing		76.87	CHF/ kg magnets, Laptop in Switzerland					
						Average costs in Switzerland for manual processing		47.85	CHF / kg magnets in CH					
						Mechanical processing								
						Economy mechanical processed HDD	Netherland	1.2	Euro / kg mechanical processing HDD			Sprecher, 2014		because no data on Switzerland, the hourly labour costs are similar (Eurostat, 2012); Value for Norway: (Trading Economics, 2016)
						Weight HDD, Desktop-PC		542	g / 1 HDD			(Ueberschaar, 2015)		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Weight HDD , Laptop		134	g / 1 HDD			(Ueberschaar, 2015)		
						Average weight Nd2Fe14B / HDD Desktop		11.45285714	g $Nd_2Fe_{14}B$ / HDD	11.45285714	g $Nd_2Fe_{14}B$ / HDD	own calculation	range: 10.286g - 12.62g	
						Average weight Nd2Fe14B / HDD Laptop		3.7375	g $Nd_2Fe_{14}B$ / HDD	3.7375	g $Nd_2Fe_{14}B$ / HDD	own calculation	range: 2.5g - 4.975g	
						Average magnet, PC weight		21.13073274	g $Nd_2Fe_{14}B$ / kg HDD					
						Average magnet, Laptop weight		27.89179104	g $Nd_2Fe_{14}B$ / kg HDD					
						Share Desktop in Switzerland		0.495	share					
						Share Laptop in Switzerland		0.505	share					
						Average magnet, Switzerland		24.5445676	g $Nd_2Fe_{14}B$ / kg HDD, CH					
						Average costs in Switzerland for shredding		0.029453481	Euro / kg mechanical processing magnets					
						Conversion factor, CHF to USD		1.01884				XE, 2016 conversion calculator	1,00 CHF = 1,01884 USD	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Conversion factor, Euro to USD		1.11706				XE, 2016 conversion calculator	1 Euro to 1.1171 USD	
						Economy manual processing costs	**Switzerland**	**49**	**$/ kg magnets, CH**			**Own calculation**		
						Economy mechanical processed HDD	**Netherland**	**0.033**	**$ / kg mechanical processing magnets, CH**			**Own calculation**		
						Labour costs	Switzerland	1.187	decimal	118.7	%		Trading Economics, 2016	
						Price level	Switzerland	1.46	decimal	146	%	OECD, 2016, https://data.oecd.org/price/price-level-indices.htm		**Norway instead of Switzerland**
Indexed cost volatility in a country														
Manual processing, costs	Switzerland	110	%	Own calculation		Economy manual processing costs	Switzerland	48.76	$/ kg magnets, CH				Calculation is costs above	Data sources range from 2011 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Mechanical processing, costs	Switzerland	110	%	Own calculation		Economy mechanical processed HDD	Netherland	0.03	$ / kg mechanical processing magnets, CH					Data sources range from 2011 - 2016. From this source (that includes many countries) no value was available from Switzerland, consequently Norway's value were used to approximate Switzerland's labour costs.
						2015: Labour costs	Switzerland	1.19	decimal	118.7	%	Trading Economics, 2016		Norway instead of Switzerland
						2011: Labour costs	Switzerland	1.05	decimal	105.25	%	Trading Economics, 2016		Norway instead of Switzerland
						2015: Price level	Switzerland	1.46	decimal	146	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm		
						2011: Price level	Switzerland	1.50	decimal	150	%	OECD, 2017, https://data.oecd.org/price/price-level-indices.htm		
Society														
Human rights implications														
Freedom of speech														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Manual and mechanical processing, Switzerland	Switzerland	99.01	%	(World Bank, 2016)									Indicator: WGI: Voice and Accountability (VA), 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Political stability														
Political stability														
Manual and mechanical processing, Switzerland	Switzerland	95.2	%	(World Bank, 2016)									Indicator: WGI: political stability and absence of violence/terrorism, 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest)	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
													rank)	
Environment														
Environmental regulatory quirement														
Environmental regulations and standards														
Manual and mechanical processing, Switzerland	Switzerland	1	-	(Cenelec 50625-2, 2015)									1' means existing environmental regulations and standards, such as ISO 14001, whereas '0' non-existing environmental regulations and standards.	
Total environmental impacts														
ReCiPe: Ecosystem and Hu-														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
man health														
Manual processing, Switzerland	Switzerland	0.599436372	Pt	(Wolfensberger, 2015)								(Wolfensberger, 2015)		
Mechanical processing, Switzerland	Switzerland	0.815327384	Pt	(Wolfensberger, 2015)								(Wolfensberger, 2015)		
Metallurgical Extraction														
Geological knowledge														
Annual mass flow														
Metallurgical extracting manual processing Desktop PC	Japan	1.16	t Nd_2O_3			Quantity Manual processing magnets, Desktop-PC	Switzerland	1.29	t Nd_2O_3			own calculation		
Metallurgical extracting manual processing Laptop	Japan	0.39	t Nd_2O_3			Quantity Manual processing magnets, Laptops	Switzerland	0.43	t Nd_2O_3			own calculation		
Metallurgical extracting mechani-	Japan	0.13	t Nd_2O_3			Quantity mechanical processing	Switzerland	0.14	t Nd_2O_3			own calculation		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
cal processing HDD Desktop-PC						HDD Desktop-PC								
Metallurgical extracting mechanical processing HDD Laptop	Japan	0.04	t Nd_2O_3			Quantity mechanical processing HDD Laptop	Switzerland	0.05	t Nd_2O_3			own calculation		
Metallurgical extracting manual processing Desktop PC	Germany	1.16	t Nd_2O_3			Recovery rate Met. Extracting Accessibility	Japan	90	%			Gupta et al. 2005		
Metallurgical extracting Manual processing Laptop	Germany	0.39	t Nd_2O_3				Germany	90	%			Gupta et al. 2005		
Metallurgical extracting mechanical processing HDD Desktop-PC	Germany	0.13	t Nd_2O_3				Austria	90	%			Gupta et al. 2005		
Metallurgical extracting mechanical pro-	Germany	0.04	t Nd_2O_3				Vietnam	90	%			Talens Peiró, 2013, p. 1338		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
cessing HDD Laptop														
Metallurgical extracting manual processing Desktop PC	Austria	1.16	t Nd_2O_3											
Metallurgical extracting manual processing Laptop	Austria	0.39	t Nd_2O_3											
Metallurgical extracting mechanical processing HDD Desktop-PC	Austria	0.13	t Nd_2O_3											
Metallurgical extracting mechanical processing HDD Laptop	Austria	0.04	t Nd_2O_3											
Metallurgical extracting manual processing Desktop	Vietnam	1.16	t Nd_2O_3											

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
PC														
Metallurgical extracting manual processing Laptop	Vietnam	0.39	t Nd_2O_3											
Metallurgical extracting mechanical processing HDD Desktop-PC	Vietnam	0.13	t Nd_2O_3											
Metallurgical extracting mechanical processing HDD Laptop	Vietnam	0.04	t Nd_2O_3											
Metallurgical extracting, manual processing, Switzerland	Switzerland	NAV	t Nd_2O_3	(Böni, 2015)										
Metallurgical extracting, shredded, Switzerland	Switzerland	NAV	t Nd_2O_3	(Böni, 2015)										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Metallurgical extracting manual processing, Japan	Japan	1.55	t Nd_2O_3	own calculation										Data sources range from 1005 to 2013
Metallurgical extracting shredded, Japan	Japan	0.17	t Nd_2O_3	own calculation										
Metallurgical extracting manual processing, Germany	Germany	1.55	t Nd_2O_3	own calculation										
Metallurgical extracting shredded, Germany	Germany	0.17	t Nd_2O_3	own calculation										
Metallurgical extracting manual processing, Austria	Austria	1.55	t Nd_2O_3	own calculation										
Metallurgical extracting shredded, Austria	Austria	0.17	t Nd_2O_3	own calculation										
Metallurgical extracting manual processing,	Vietnam	1.55	t Nd_2O_3	own calculation										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Vietnam														
Metallurgical extracting shredded, Vietnam	Vietnam	0.17	t Nd_2O_3	own calculation										
Mass fraction														
Metallurgical extracting, Switzerland	Switzerland	NAV	-	(Böni, 2015)										
Metallurgical extracting, Japan	Japan	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al., 2015)									Since no value was available and the processes are the same, the values of geogenic mining were used.	
Metallurgical extracting, Germany	Germany	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al., 2015)									Since no value was available and the processes are the same, the values of geogenic mining were used.	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Metallurgical extracting, Austria	Austria	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al., 2015)									Since no value was available and the processes are the same, the values of geogenic mining were used.	
Metallurgical extracting, Vietnam	Vietnam	85	% tREO / t material	(Simoni et al., 2015; Wolfensberger et al., 2015)									Since no value was available and the processes are the same, the values of geogenic mining were used.	
Eligibility														
Market concentration														
Metallurgical extracting, Switzerland	Switzerland	NAV	-	(Böni, 2015)									Opportunities were discussed theoretically only	
Metallurgical extracting, Japan	Japan	NAV	-	(Bunge, 2015)										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Metallurgical extracting, Germany	Germany	NAV	-	(Bunge, 2015)										
Metallurgical extracting, Austria	Austria	NAV	-	(Bunge, 2015)										
Metallurgical extracting, Vietnam	Vietnam	NAV	-	(Bunge, 2015)										
Operating license														
Metallurgical extracting, Switzerland	Switzerland	NAV	-	(Böni, 2015)									1' means existing operating license, whereas '0' non-existing operating license.	
Metallurgical extracting, Japan	Japan	1	-	(Bunge, 2015)										Data value for entire Japan.
Metallurgical extracting, Germany	Germany	1	-	(Bunge, 2015)										Data value for entire Germany.
Metallurgical extracting, Austria	Austria	1	-	(Bunge, 2015)										Data value for entire Austria.
Metallurgical extracting, Vietnam	Vietnam	1	-	(Bunge, 2015)										Data value for entire Vietnam.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Technology														
Knowledge of machine and infrastructure														
Metallurgical extracting, Switzerland	Switzerland	0	-	(Bunge, 2015)									Quantify: weather knowledge does not exists (0), is in research (1) or scale up-phase (2) or large scale production (3).	Data value for entire Switzerland.
Metallurgical extracting, Japan	Japan	3	-	(Bunge, 2015)										Data value for entire Japan.
Metallurgical extracting, Germany	Germany	3	-	(Bunge, 2015)										Data value for entire Germany.
Metallurgical extracting, Austria	Austria	3	-	(Bunge, 2015)										Data value for entire Austria.
Metallurgical extracting, Vietnam	Vietnam	3	-	(Bunge, 2015)										Data value for entire Vietnam.
Indexed annual rate of collection, mining re-														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
covery and processing recovery														
Metallurgical extracting, manual, Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Metallurgical extracting, mechanical (mechanical processing), Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Metallurgical extracting, Japan	Japan	91	%	Own calculation		Recovery rate Met. Extraction	Metallurgical extracting Malaysia (LAMP) for Monazite by Rhône-Poulenc	90	%			Gupta et al. 2005	Since this process is well established, we assumed very similar conditions for the processing of magnets	Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Metallurgical extracting, Germany	Germany	92	%	Own calculation		Metallurgical extracting Malaysia (LAMP) for Monazite by Rhône-Poulenc	90	%				Talens Peiró, 2013, p. 1338		Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Metallurgical extracting, Austria	Austria	91	%	Own calculation			Japan	1.02	-			INSEAD, 2015 & normalised values to range between 0.5% to 2%.		Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Metallurgical extracting, Vietnam	Vietnam	91	%	Own calculation			Germany	1.02	-			INSEAD, 2015 & normalised values to range between 0.5% to 2%.	Since this process is well established, we assumed very similar conditions for the processing of magnets	Data values from 2005 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
							Austria	1.02	-			INSEAD, 2015 & normalised values to range between 0.5% to 2%.		
							Vietnam	1.01	-			INSEAD, 2015 & normalised values to range between 0.5% to 2%.		
Economy														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Indexed costs in a country														
Metallurgical extracting, manual, Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Metallurgical extracting, mechanical (mechanical processing), Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Metallurgical extracting, Japan	Japan	NAV	'-	'-	Processing costs	Metallurgical Extraction of magnets		NAV	Euro / kg Nd2Fe14B magnets				Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam;	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
													for the price level source Indonesia was used to proximate Vietnam.	
Metallurgical extracting, Germany	Germany	NAV	'-	'-		Labour costs	Japan	1.294	decimal	129.4	%	Trading Economics, 2016	South Korea is the closest proxy for Japan.	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Metallurgical extracting, Austria	Austria	NAV	'-	'-			Germany	1.1064	decimal	110.64	%	Trading Economics, 2016	Data from Dec. 2015	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Metallurgical extracting, Vietnam	Vietnam	NAV	'-	'-			Austria	1.108	decimal	110.8	%	Trading Economics, 2016	Taiwan is the closest proxy for Vietnam	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
														was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
							Vietnam	0.9523	decimal	95.23	%	Trading Economics, 2016	100 = OECD, all other countries are a relative thereof	
						Price level	Japan	0.97	decimal	97	%	OECD, 2016		
							Germany	0.97	decimal	97	%	OECD, 2016		
							Austria	1.01	decimal	101	%	OECD, 2016		
							Vietnam	0.35	decimal	35	%	OECD, 2016	Indonesia is the closest proxy for Vietnam	
Indexed cost volatility in a country														
Metallurgical extracting, manual, Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Metallurgical extracting,	Switzerland	NAV	-	(Bunge, 2015)										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
mechanical (shred-(shredding), Switzerland														
Metallurgical extracting, Japan	Japan	NAV	'-	'-		Processing costs	Metallurgical Extraction of magnets	NAV	Euro / kg Nd2Fe14B magnets			Sprecher et al. 2014	- The total EoL magnets price is 10 Euro, but we have two processes. Because there is not processing but we will intend to reflect two steps, the 10 Euro was split into Euro for each process. Calculation: Multiplication of costs / kg with decimal value. Justification: price changes slightly while reflecting the labour costs of a	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
													country. '- Since rough calculation, same data assumed for 2011.	
Metallurgical extracting, Germany	Germany	NAV	'-	'-		1015: Labour costs	Japan	1.31	decimal	131	%	Trading Economics, 2016	South Korea is the closest proxy for Japan.	
Metallurgical extracting, Austria	Austria	NAV	'-	'-			Germany	1.09	decimal	109	%	Trading Economics, 2016		Data from Dec. 2015
Metallurgical extracting, Vietnam	Vietnam	NAV	'-	'-			Austria	1.10	decimal	110	%	Trading Economics, 2016		
							Vietnam	1.09	decimal	109	%	Trading Economics, 2016	Taiwan is the closest proxy for Vietnam	
						1011: Labour costs	Japan	1.00	decimal	100	%	Trading Economics, 2016	South Korea is the closest proxy for Japan	
							Germany	1.00	decimal	100	%	Trading Economics, 2016		Data from Dec. 2015
							Austria	1.01	decimal	101	%	Trading Economics, 2016	Taiwan is the closest proxy for Vietnam	
							Vietnam	0.81	decimal	81	%	Trading Economics, 2016	100 = OECD, all other countries	

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
													are a relative thereof	
						2015: Price level	Japan	0.96	decimal	96	%	OECD, 2016		
							Germany	0.97	decimal	97	%	OECD, 2016		
							Austria	1.00	decimal	100	%	OECD, 2016		
							Vietnam	0.35	decimal	35	%	OECD, 2016	Indonesia is the closest proxy for Vietnam	
						2011: Price level	Japan	1.28	decimal	128	%	OECD, 2016		
							Germany	1.04	decimal	104	%	OECD, 2016		
							Austria	1.10	decimal	110	%	OECD, 2016		
							Vietnam	0.35	decimal	35	%	OECD, 2016	Indonesia is the closest proxy for Vietnam	
Society														
Human rights implications														
Freedom of speech														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Metallurgical extracting, Switzerland	Switzerland	NAV											Process does not exist	
Metallurgical extracting, Japan	Japan	79.31	%	(World Bank, 2016)										
Metallurgical extracting, Germany	Germany	95.57	%	(World Bank, 2016)										
Metallurgical extracting, Austria	Austria	94.58	%	(World Bank, 2016)										
Metallurgical extracting, Austria	Vietnam	10.84	%	(World Bank, 2016)										
Political stability														
Political stability														
Metallurgical extracting, Switzerland	Switzerland	NAV	-										Process does not exist	
Metallurgical extracting, Japan	Japan	82.4	%	(World Bank, 2016)									Finland was used as a proxy for Japan.	
Metallurgical extracting, Germany	Germany	70.0	%	(World Bank, 2016)										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Metallurgical extracting, Austria	Austria	90.5	%	(World Bank, 2016)										
Metallurgical extracting, Vietnam	Vietnam	48.6	%	(World Bank, 2016)									Hungary was used as a proxy for Vietnam.	
Environment														
Environmental regulatory quirement														
Environmental regulations and standards														
Metallurgical extracting, Switzerland	Switzerland	NAV	-										1' means existing environmental regulations and standards, such as ISO 14001, whereas '0' non-existing environmental regulations and standards.	Data sources range from 1998 - 2017.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Metallurgical extracting, Japan	Japan	1	-	(Hitachi, 2017)										Data sources range from 1998 - 2017.
Metallurgical extracting, Germany	Germany	1	-	(Loser Chemie, 2017)										Data sources range from 1998 - 2017.
Metallurgical extracting, Austria	Austria	1	-	(Chevron, 1998)										Data sources range from 1998 - 2017.
Metallurgical extracting, Vietnam	Vietnam	0	-	-									No information on the company available.	Data sources range from 1998 - 2017. No information online available, thus assumed to have no certification for environmental standards.
Total environmental impacts														
ReCiPe: Ecosystem and Human health														
Metallurgical extracting, manual, Switzerland	Switzerland	NAV	-	-									No information publically available	
Metallurgical extracting, mechanical (shred-(shredding), Switzer-	Switzerland	NAV	-	-									No information publically available	Data value accounts also for refining.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
land														
Metallurgical extracting, Japan	Japan	NAV	-	-									No information publically available	
Metallurgical extracting, Germany	Germany	NAV	-	-									No information publically available	Data value accounts also for refining and carried out in
Metallurgical extracting, Austria	Austria	NAV	-	-									No information publically available	Data value accounts also for refining and carried out in
Metallurgical extracting, Vietnam	Vietnam	NAV	-	-									No information on the company available.	
Refining														
Geological knowledge														
Annual mass flow														
Refining Manual processing Desktop PC	Japan	1.04	t Nd_2O_3	own calculation		Metallurgical extracting manual processing Desktop PC	Japan	1.160676	t Nd2O3			own calculation		
Refining Manual processing	Japan	0.35	t Nd_2O_3	own calculation		Metallurgical extracting manual	Japan	0.38631	t Nd2O3			own calculation		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Laptop						processing Laptop								
Refining mechanical processing HDD Desktop-PC	Japan	0.12	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD Desktop-PC	Japan	0.128964	t Nd2O3			own calculation		
Refining mechanical processing HDD Laptop	Japan	0.04	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD Laptop	Japan	0.042923	t Nd2O3			own calculation		
Refining Manual processing Desktop PC	Germany	1.04	t Nd_2O_3	own calculation		Metallurgical extracting manual processing Desktop PC	Germany	1.160676	t Nd2O3			own calculation		
Refining Manual processing Laptop	Germany	0.35	t Nd_2O_3	own calculation		Metallurgical extracting Manual processing Laptop	Germany	0.38631	t Nd2O3			own calculation		
Refining mechanical processing HDD Desktop-PC	Germany	0.12	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD	Germany	0.128964	t Nd2O3			own calculation		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						Desktop-PC								
Refining mechanical processing HDD Laptop	Germany	0.04	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD Laptop	Germany	0.042923	t Nd2O3			own calculation		
Refining Manual processing Desktop PC	Austria	1.04	t Nd_2O_3	own calculation		Metallurgical extracting manual processing Desktop PC	Austria	1.160676	t Nd2O3			own calculation		
Refining Manual processing Laptop	Austria	0.35	t Nd_2O_3	own calculation		Metallurgical extracting manual processing Laptop	Austria	0.38631	t Nd2O3			own calculation		
Refining mechanical processing HDD Desktop-PC	Austria	0.12	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD Desktop-PC	Austria	0.128964	t Nd2O3			own calculation		
Refining mechanical processing HDD Laptop	Austria	0.04	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD Lap-	Austria	0.042923	t Nd2O3			own calculation		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						top								
Refining Manual processing Desktop PC	Vietnam	1.04	t Nd_2O_3	own calculation		Metallurgical extracting manual processing Desktop PC	Vietnam	1.160676	t Nd2O3			own calculation		
Refining Manual processing Laptop	Vietnam	0.35	t Nd_2O_3	own calculation		Metallurgical extracting manual processing Laptop	Vietnam	0.38631	t Nd2O3			own calculation		
Refining mechanical processing HDD Desktop-PC	Vietnam	0.12	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD Desktop-PC	Vietnam	0.128964	t Nd2O3			own calculation		
Refining mechanical processing HDD Laptop	Vietnam	0.04	t Nd_2O_3	own calculation		Metallurgical extracting mechanical processing HDD Laptop	Vietnam	0.042923	t Nd2O3			own calculation		
Refining, manual processing, Switzerland	Switzerland	NAV	t Nd_2O_3	(Böni, 2015)		Recovery rate Met. Extracting Accessibility	Japan	90	%			Talens Peiró, 2013, p. 1338		

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Refining, mechanical processing, Switzerland	Switzerland	NAV	t Nd_2O_3	(Böni, 2015)			Germany	90	%			Talens Peiró, 2013, p. 1338		
Refining manual processing, Japan	Japan	1.39	t Nd_2O_3	own calculation			Austria	90	%			Talens Peiró, 2013, p. 1338		
Refining mechanical processing, Japan	Japan	0.15	t Nd_2O_3	own calculation			Vietnam	1	%			INSEAD, 2015 & normalised values to range between 0.5% to 2%.		
Refining manual processing, Germany	Germany	1.39	t Nd_2O_3	own calculation										
Refining mechanical processing, Germany	Germany	0.15	t Nd_2O_3	own calculation										
Refining manual processing, Austria	Austria	1.39	t Nd_2O_3	own calculation										
Refining mechanical processing, Austria	Austria	0.15	t Nd_2O_3	own calculation										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Refining manual processing, Vietnam	Vietnam	1.39	t Nd_2O_3	own calculation										
Refining mechanical processing, Vietnam	Vietnam	0.15	t Nd_2O_3	own calculation										
Mass fraction														
Refining, Switzerland	Switzerland	NAV	-	(Böni, 2015)										
Refining , Japan	Japan	99.5	% tNd_2O_3 / t material	(USGS, 2016)										Since no value was available and the processes are the same, the values of geogenic mining were used.
Refining , Germany	Germany	99.5	% tNd_2O_3 / t material	(USGS, 2016)										Since no value was available and the processes are the same, the values of geogenic mining were used.
Refining , Austria	Austria	99.5	% tNd_2O_3 / t material	(USGS, 2016)										Since no value was available and the processes are the same, the values of geogenic mining were used.
Refining , Japan	Vietnam	99.5	% tNd_2O_3 / t material	(USGS, 2016)										Since no value was available and the processes are the same, the values of geogenic mining were used.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Eligibility														
Market concentration														
Refining, Switzerland	Switzerland	NAV	-	(Böni, 2015)									Opportunities were discussed theoretically only	
Refining, Japan	Japan	NAV	-	(Bunge, 2015)										
Refining, Germany	Germany	NAV	-	(Bunge, 2015)										
Refining, Austria	Austria	NAV	-	(Bunge, 2015)										
Refining, Vietnam	Vietnam	NAV	-	(Bunge, 2015)										
Operating license														
Refining, Switzerland	Switzerland	NAV	-	(Böni, 2015)									1' means existing operating license, whereas '0' non-existing operating license.	
Refining, Japan	Japan	1	-	(Bunge, 2015)										Data value for entire Japan.
Refining, Germany	Germany	1	-	(Bunge, 2015)										Data value for entire Germany.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Refining, Austria	Austria	1	-	(Bunge, 2015)										Data value for entire Austria.
Refining, Vietnam	Vietnam	1	-	(Bunge, 2015)										Data value for entire Vietnam.
Technology														
Knowledge of machine and infrastructure														
Refining, Switzerland	Switzerland	0	-	(Bunge, 2015)									Quantify: weather knowledge does not exists (0), is in research (1) or scale up-phase (2) or large scale production (3).	Data value for entire Switzerland
Refining, Japan	Japan	3	-	(Bunge, 2015)										Data value for entire Japan.
Refining, Germany	Germany	3	-	(Bunge, 2015)										Data value for entire Germany.
Refining, Austria	Austria	3	-	(Bunge, 2015)										Data value for entire Austria.
Refining, Vietnam	Vietnam	3	-	(Bunge, 2015)										Data value for entire Vietnam.
Indexed annual rate of														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
collection, mining recovery and processing recovery														
Refining, manual, Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Refining, mechanical (mechanical processing), Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Refining, Japan	Japan	91	%	Own calculation		Solvent extraction, precipitation	Precipitation and multiple solvent extraction	90	%			Talens Peiró, 2013, p. 1338	Since this process is well established, we assumed very similar conditions for the processing of magnets	Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Refining, Germany	Germany	92	%	Own calculation			Japan	1.02	-			INSEAD, 2015 & normalised values to range between 0.5% to 2%.		Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
Refining, Austria	Austria	91	%	Own calculation		Innovation Efficiency Ra-	Germany	1.02	-			INSEAD, 2015 & normal-		Data values from 2013 to 2015 and innovation efficiency

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
						tio --> how much innovation is given for it's inputs						ised values to range between 0.5% to 2%.		value was normalised to a range from 0.5% to 2%.
Refining, Vietnam	Vietnam	91	%	Own calculation			Austria	1.02				INSEAD, 2015 & normalised values to range between 0.5% to 2%.		Data values from 2013 to 2015 and innovation efficiency value was normalised to a range from 0.5% to 2%.
				Own calculation			Vietnam	1.01				INSEAD, 2015 & normalised values to range between 0.5% to 2%.		
Economy														
Indexed costs in a country														
Refining, manual, Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Refining, mechanical (mechanical processing), Switzerland	Switzerland	NAV	-	(Bunge, 2015)										

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Refining, Japan	Japan	46	$\$/\text{kg Nd}_2\text{O}_3$	Own calculation		Processing costs	Precipitation global	37	\$/kg Nd2O3			USGS, 2016, Rare Earth data set		Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Refining, Germany	Germany	40	$\$/\text{kg Nd}_2\text{O}_4$	Own calculation		Labour costs	Japan	1.294	decimal	129.4	%	Trading Economics, 2016	South Korea is the closest proxy for Japan.	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Refining, Austria	Austria	41	$\$/\text{kg Nd}_2\text{O}_5$	Own calculation			Germany	1.1064	decimal	110.64	%	Trading Economics, 2016	Data from Dec. 2015	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Refining, Vietnam	Vietnam	12	$/kg Nd_2O_6	Own calculation			Austria	1.108	decimal	110.8	%	Trading Economics, 2016	Data from Dec. 2015	Data sources range from 2015 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
							Vietnam	0.9523	decimal	95.23	%	Trading Economics, 2016	Taiwan is the closest proxy for Vietnam	
						Price level	Japan	0.97	decimal	97	%	OECD, 2016	100 = OECD, all other countries are a relative thereof	
							Germany	0.97	decimal	97	%	OECD, 2016		
							Austria	1.01	decimal	101	%	OECD, 2016		
							Vietnam	0.35	decimal	35	%	OECD, 2016	Indonesia is the closest proxy for Vietnam	
Indexed cost volatility in a country														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Refining, manual, Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Refining, mechanical (shred-(shredding), Switzerland	Switzerland	NAV	-	(Bunge, 2015)										
Refining, Japan	Japan	98.09	%	Own Calculation			Precipitation global	37	$/kg Nd2O3			USGS, 2016, Rare Earth data set		Data sources range from 2011 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Refining, Germany	Germany	100.87	%	Own Calculation		2015: Labour costs	Japan	1.31	decimal	131	%	Trading Economics, 2016	South Korea is the closest proxy for Japan	Data sources range from 2011 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Refining, Austria	Austria	99.44	%	Own Calculation			Germany	1.09	decimal	109	%	Trading Economics, 2016	Data from Dec. 2015	Data sources range from 2011 - 2016. From the labour

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
														costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
Refining, Vietnam	Vietnam	134.29	%	Own Calculation			Austria	1.10	decimal	110	%	Trading Economics, 2016	Data from Dec. 2015	Data sources range from 2011 - 2016. From the labour costs source (that includes many countries) South Korea was used to proximate Japan; congruently Taiwan to proximate Vietnam; for the price level source Indonesia was used to proximate Vietnam.
							Vietnam	1.09	decimal	109	%	Trading Economics, 2016	Taiwan is the closest proxy for Vietnam	
						2011: Labour costs	Japan	1.00	decimal	100	%	Trading Economics, 2016	South Korea is the closest proxy for Japan	
							Germany	1.00	decimal	100	%	Trading Economics, 2016		Data from Dec. 2015
							Austria	1.01	decimal	101	%	Trading Economics, 2016		Data from Dec. 2015

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
							Vietnam	0.81	decimal	81	%	Trading Economics, 2016	Taiwan is the closest proxy for Vietnam	
						2015: Price level	Japan	0.96	decimal	96	%	OECD, 2017	100 = OECD, all other countries are a relative thereof	
							Germany	0.97	decimal	97	%	OECD, 2017		
							Austria	1.00	decimal	100	%	OECD, 2017		
							Vietnam	0.35	decimal	35	%	OECD, 2017	Indonesia is the closest proxy for Vietnam	
						2011: Price level	Japan	1.28	decimal	128	%	OECD, 2017	100 = OECD, all other countries are a relative thereof	
							Germany	1.04	decimal	104	%	OECD, 2017		
							Austria	1.10	decimal	110	%	OECD, 2017		
							Vietnam	0.35	decimal	35	%	OECD, 2017	Indonesia is the closest proxy for Vietnam	
Society														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Human rights implications														
Freedom of speech														
Refining, Switzerland	Switzerland	NAV	-	-									Indicator: WGI: Voice and Accountability (VA), 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Refining, Japan	Japan	79.31	%	(World Bank, 2016)										
Refining, Germany	Germany	95.57	%	(World Bank, 2016)										
Refining, Austria	Austria	94.58	%	(World Bank, 2016)										
Refining, Vietnam	Vietnam	10.84	%	(World Bank, 2016)										
Political stability														
Political stability														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Refining, Switzerland	Switzerland	-	%	-									Indicator: WGI: political stability and absence of violence/terrorism, 2015 data; Unit: Percentile rank among all countries (ranges from 0 (lowest) to 100 (highest) rank)	
Refining, Japan	Japan	82.4	%	(World Bank, 2016)									Finland was used as a proxy for Japan.	
Refining, Germany	Germany	70.0	%	(World Bank, 2016)										
Refining, Austria	Austria	90.5	%	(World Bank, 2016)										
Refining, Vietnam	Vietnam	48.6	%	(World Bank, 2016)									Hungary was used as a proxy for Vietnam.	
Environment														
Environmental regulatory														

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
quire-ment														
Environmental regulations and standards														
Refining, Switzerland	Switzerland	NAV	-	-									1' means existing environmental regulations and standards, such as ISO 14001, whereas '0' non-existing environmental regulations and standards.	Data sources range from 1998 - 2017.
Refining, Japan	Japan	1	-	(Hitachi, 2017)										Data sources range from 1998 - 2017.
Refining, Germany	Germany	1	-	(Loser Chemie, 2017)										Data sources range from 1998 - 2017.
Refining, Austria	Austria	1	-	(Chevron, 1998)										Data sources range from 1998 - 2017.
Refining, Vietnam	Vietnam	0	-	-									No information on the company available.	Data sources range from 1998 - 2017. No information online available, thus assumed to have no certification for environmental standards.

Indicator	Location	Value	Unit	Reference	Comment	Sub-indicator	Location	Value	Unit	Value original	Unit	Reference	Remark	Assumptions
Total environmental impacts														
ReCiPe: Ecosystem and Human health														
Refining, manual, Switzerland	Switzerland	NAV	-	-									No information publically available	Data value accounts also for metallurgical extracting.
Refining, mechanical (shred-(shredding), Switzerland	Switzerland	NAV	-	-									No information publically available	Data value accounts also for metallurgical extracting.
Refining, Japan	Japan	NAV	-	-									No information publically available	
Refining, Germany	Germany	NAV	-	-									No information publically available	Data value accounts also for metallurgical extracting.
Refining, Austria	Austria	NAV	-	-									No information publically available	Data value accounts also for metallurgical extracting.
Refining, Vietnam	Vietnam	NAV	-	-									No information on the company available.	

G.9 Framework consolidation: Uncertainty, respectively: data quality rating (DQR)

Table 33: Pedigree matrix explanation of the quality of data source evaluation.

Indicator score	1 (high)	2	3	4	5 (low)
Reliability (R) that states, whether the data bases on measurement or non-qualified estimate.	Verified [33]data based on quantitative and qualitative (e.g. survey) **measurements** [34]	Verified data based **partly on assumptions** or **non-verified data based on measurements**	Non-verified data **partly based** on **qualified estimates**	Qualified estimate (e.g. by **industrial expert**)	**Non-qualified estimate**
Completeness (Co), which evaluates whether the data was complete from a predefined area over an adequate period or the data was unknown or incomplete.	Representative data from a **continues sample** for a **predefined area over an adequate period**	Representative data from a sample for a different **predefined area** but **for adequate periods**	Representative data from a sample for a different **predefined area a country but from shorter periods**	Representative data but from a sample for a different **predefined area and shorter periods or incomplete data from an adequate number of sites and periods**	Representativeness **unknown or incomplete data** from a sample for a predefined area and/or from shorter periods
Temporal correlation (TeC) ranks whether the data is less than one year difference to the year of study or more than ten.	**Less than 1** years of difference to year of study[35]	**Less than 2** years of difference	**Less than 3** years of difference	**Less than 5** years of difference	Age of data **unknown or more than 10 years** of difference
Geographical correlation (GC) assesses whether the	Data from **area under study**[36]	Average data from **larger area** in which the **area un-**	Data from area with **similar collecting, mining and**	Data from area with **slightly similar** collecting,	Data from **unknown area or area with very different collect-**

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[33] Verification may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances, or cross-checks with other sources.

[34] Includes calculated data (e.g. emissions calculated from inputs to an activity), when the basis for calculation is measurements (e.g. measured inputs). If the calculation is based partly on assumptions, the score would result in 2 or 3.

[35] The temporal base year for the study was 2015

[36] Spatial scope for the study was Switzerland, Germany, Austria, Japan, Vietnam, China, Australia and the USA.

Indicator score	1 (high)	2	3	4	5 (low)
data are from an area under study or from an unknown area.		**der study is included**	**production conditions**	mining and production conditions	**ing**, mining and production conditions

G.10 Framework application, results and discussion: detailed data quality ranking of mining deposits in the geosphere

Figure 31 Results from Data Quality ranking from quantifying MDG (mining deposits in the geosphere) along the operational steps. R stands for reliability, Co for Completeness, GC for Geographical Correlation and TeC for Temporal Correlation.

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Referer-ence year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
Geological knowledge	Quantity	Mass	Mining, Mt. Weld	Australia	own calculation		2015	1.00	High	1	1	1	1
			Mining, Bayan Obo	China	own calculation		2015	2.88	Fair	1	1	4	1
			Mining, Mt. Pass	USA	own calculation		2014	1.63	Fair	1	1	1	2
			Mineral processing, Mt. Weld	Australia	own calculation		2015	1.63	Fair	2	1	1	1
			Mineral processing, Bayan Obo	China	own calculation		2015	1.75	Fair	2	1	2	1
			Mineral processing, Mt. Pass	USA	own calculation		2015	1.75	Fair	2	2	1	1
			Metallurgical extraction, Mt. Weld and Malaysia	Malaysia	own calculation		2015	1.63	Fair	2	1	1	1
			Metallurgical extraction, Bayan Obo	China	own calculation		2015	1.75	Fair	2	1	2	1
			Metallurgical extraction, Mt. Pass	USA	own calculation		2015	1.75	Fair	2	2	1	1
			Refining, Mt. Weld	Malaysia	(Machacek, 2015, p. 85)		2015	1.63	Fair	2	1	1	1
			Refining, Bayan Obo	China	own calculation		2015	1.75	Fair	2	1	2	1
			Refining, Mt. Pass, first quarter of 2015	USA	own calculation		2015	1.75	Fair	2	2	1	1
	Quality	Mass fraction	Mining, Mt. Weld	Australia	(Wall, 2014)		2014	2.75	Fair	3	2	3	2

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Refererence year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Mining, Bayan Obo	China	(Wall, 2014)		2014	2.75	Fair	3	2	3	2
			Mining, Mt. Pass	USA	(Wall, 2014)		2014	2.75	Fair	3	2	3	2
			Mineral processing, Mt. Weld	Australia	(Jaireth and Hoatson, 2014)		2014	2.38	Fair	2	1	1	3
			Mineral processing, Bayan Obo	China	(Zhi Li, 2014, Machacek 2015)		2014	1.88	Fair	2	1	2	2
			Mineral processing, Mt. Pass	USA	(Habib, 2014)		2014	2.38	Fair	2	1	1	3
			Metallurgical extraction, Mt. Weld and Malaysia	Malaysia	(Simoni, 2015)		2014	2.75	Fair	3	2	3	2
			Metallurgical extraction, Bayan Obo	China	(Simoni, 2015)		2014	2.75	Fair	3	2	3	2
			Metallurgical extraction, Mt. Pass	USA	(Simoni, 2015)		2014	2.75	Fair	3	2	3	2
			Refining, Mt. Weld	Malaysia	(USGS, 2016)		2015	2.25	Fair	1	1	3	1
			Refining, Bayan Obo	China	(USGS, 2016)		2015	2.25	Fair	1	1	3	1
			Refining, Mt. Pass	USA	(USGS, 2016)		2015	2.25	Fair	1	1	3	1
Eligibility	Ownership	Market concentration	Mining, Mt. Weld	Australia	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Mining, Bayan Obo	China	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Mining, Mt. Pass	USA	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Mineral processing, Mt. Weld	Australia	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Mineral processing, Bayan Obo	China	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Mineral processing,	USA	USGS,		2015	1.88	Fair	2	2	2	1

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Refererence year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Mt. Pass		2016, p. 135								
			Metallurgical extraction, Mt. Weld and Malaysia	Malaysia	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Metallurgical extraction, Bayan Obo	China	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Metallurgical extraction, Mt. Pass	USA	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Refining, Mt. Weld	Malaysia	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Refining, Bayan Obo	China	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
			Refining, Mt. Pass	USA	USGS, 2016, p. 135		2015	1.88	Fair	2	2	2	1
	Regulatory requirement	Operating license	Mining, Mt. Weld	Australia	(Schmidt, 2013)		2015	2.50	Fair	1	3	1	3
			Mining, Bayan Obo	China	(Wübbeke, 2013)		2015	2.75	Fair	2	3	2	3
			Mining, Mt. Pass	USA	(Machacek and Fold, 2014)		2015	2.38	Fair	1	3	1	2
			Mineral processing, Mt. Weld	Australia	(Schmidt, 2013)		2015	2.50	Fair	1	3	1	3
			Mineral processing, Bayan Obo	China	(Wübbeke, 2013)		2015	2.75	Fair	2	3	2	3
			Mineral processing, Mt. Pass	USA	(Machacek and Fold, 2014)		2015	2.50	Fair	1	3	2	2
			Metallurgical extracting, Mt. Weld	Malaysia	(Schmidt, 2013)		2015	2.50	Fair	1	3	1	3
			Metallurgical extracting Bayan Obo	China	(Wübbeke, 2013)		2015	2.75	Fair	2	3	2	3
			Metallurgical extracting Mt. Pass	USA	(Machacek and Fold, 2014)		2015	2.50	Fair	1	3	2	2
			Refining, Mt. Weld	Malaysia	(Schmidt, 2013)		2015	2.50	Fair	1	3	1	3

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Refererence year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Refining, Bayan Obo	China	(Wübbeke, 2013)		2015	2.75	Fair	2	3	2	3
			Refining, Mt. Pass	USA	(Machacek and Fold, 2014)		2015	2.50	Fair	1	3	2	2
Technology	Machine and infrastructure knowledge	Machine and infrastructure knowledge	Mining, Mt. Weld	Australia	(Schmidt, 2013)		2015	2.38	Fair	2	1	1	3
			Mining, Bayan Obo	China	(Wübbeke, 2013)		2015	2.50	Fair	2	1	2	3
			Mining, Mt. Pass	USA	(Machacek and Fold, 2014)		2015	1.88	Fair	2	1	2	2
			Mineral processing, Mt. Weld	Australia	(Schmidt, 2013)		2015	2.38	Fair	2	1	1	3
			Mineral processing, Bayan Obo	China	(Wübbeke, 2013)		2015	2.50	Fair	2	1	2	3
			Mineral processing, Mt. Pass	USA	(Machacek and Fold, 2014)		2015	1.88	Fair	2	1	2	2
			Metallurgical extracting, Mt. Weld	Malaysia	(Schmidt, 2013)		2015	2.38	Fair	2	1	1	3
			Metallurgical extracting Bayan Obo	China	(Wübbeke, 2013)		2015	2.50	Fair	2	1	2	3
			Metallurgical extracting Mt. Pass	USA	(Machacek and Fold, 2014)		2015	1.88	Fair	2	1	2	2
			Refining, Mt. Weld	Malaysia	(Schmidt, 2013)		2015	2.38	Fair	2	1	1	3
			Refining, Bayan Obo	China	(Wübbeke, 2013)		2015	2.50	Fair	2	1	2	3
			Refining, Mt. Pass	USA	(Machacek and Fold, 2014)		2015	1.88	Fair	2	1	2	2
	Machine and infrastructure use	Annual rate of collection, mining recovery and processing recovery	Mining, Mt. Weld	Australia	Sprecher, 2014, SI p. 3		2015	4.25	Poor	5	4	3	2
			Mining, Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	Sprecher, 2014, SI p. 3		2015	4.13	Poor	5	4	2	2
			Mining, Mt. Pass	USA, Mt Pass	Sprecher, 2014, SI p. 3		2015	4.25	Poor	5	4	3	2

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Refererence year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Mineral processing, Mt. Weld	Malaysia, LAMP Processing plant	Own calculation		2015	3.25	Poor	4	2	2	2
			Mineral processing, Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	Own calculation		2015	3.25	Poor	4	2	2	2
			Mineral processing, Mt. Pass	USA, Mt Pass	Own calculation		2015	3.25	Poor	4	2	2	2
			Metallurgical extracting, Mt. Weld	Malaysia	Own calculation		2015	3.25	Poor	4	2	2	2
			Metallurgical extracting Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	Own calculation		2015	3.25	Poor	4	2	2	2
			Metallurgical extracting Mt. Pass	USA, Mt Pass	Own calculation		2015	3.25	Poor	4	2	2	2
			Refining, Mt. Weld	Malaysia	Own calculation		2015	3.25	Poor	4	2	2	2
			Refining, Bayan Obo	China Bastnäsite from Baotou and ion adsoption clay from Southern provinces	Own calculation		2015	3.25	Poor	4	2	2	2
			Refining, Mt. Pass	USA, Mt Pass	Own calculation		2015	3.25	Poor	4	2	2	2
	Costs to a country for collecting, mining and processing	Costs to a country	Mining, Mt. Weld	Australia	NAV		2015	0	NAV				
			Mining, Bayan Obo	China	NAV		2015	0	NAV				
			Mining, Mt. Pass	USA	NAV		2015	0	NAV				
			Mineral processing, Mt. Weld	Australia	Own calculation		2015	4.00	Poor	5	2	2	3
			Mineral processing, Bayan Obo	China	Own calculation		2015	4.00	Poor	5	2	2	3
			Mineral processing, Mt. Pass	USA	Own calculation		2015	4.00	Poor	5	2	2	3
			Metallurgical extracting, Mt. Weld	Malaysia	Own calculation		2015	3.38	Poor	3	3	1	4
			Metallurgical extracting Bayan Obo	China	Own calculation		2015	3.50	Poor	3	3	2	4
			Metallurgical extracting Mt. Pass	USA	Own calculation		2015	3.38	Poor	3	3	1	4
			Refining, Mt. Weld	Malaysia	Own cal-		2015	2.38	Fair	3	2	1	1

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
					culation								
			Refining, Bayan Obo	China	Own calculation		2015	3.38	Poor	3	2	2	4
			Refining, Mt. Pass	USA	Own calculation		2015	2.38	Fair	3	2	1	1
	Cost volatility for collecting, mining and processing	Cost volatility to a country	Mining, Mt. Weld	Australia	NAV		2015	0	NAV				
			Mining, Bayan Obo	China	NAV		2015	0	NAV				
			Mining, Mt. Pass	USA	NAV		2015	0	NAV				
			Mineral processing, Mt. Weld	Australia	NAV		2015	0	NAV				
			Mineral processing, Bayan Obo	China	NAV		2015	0	NAV				
			Mineral processing, Mt. Pass	USA	NAV		2015	0	NAV				
			Metallurgical extracting, Mt. Weld	Malaysia	Own calculation		2009	3.88	Poor	2	2	2	5
			Metallurgical extracting Bayan Obo	China	Own calculation		2009	3.88	Poor	2	2	2	5
			Metallurgical extracting Mt. Pass	USA	Own calculation		2009	3.88	Poor	2	2	2	5
			Refining, Mt. Weld	Malaysia	Own calculation		2015	1.88	Fair	2	2	1	2
			Refining, Bayan Obo	China	Own calculation		2015	2.00	Fair	2	2	2	2
			Refining, Mt. Pass	USA	Own calculation		2015	1.88	Fair	2	2	1	2
Society	Human rights implications	Freedom of speech	Mining, Mt. Weld	Australia	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mining, Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mining, Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mineral processing, Mt. Weld	Australia	(World Bank,		2015	1.75	Fair	1	2	2	1

Compo-nent	Sub-component	Indicator	Name of data set	Location	Refer-ence	Remark	Refer-er-ence year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
					2016)								
			Mineral processing, Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mineral processing, Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Metallurgical extracting, Mt. Weld	Malaysia	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Metallurgical extracting Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Metallurgical extracting Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Refining, Mt. Weld	Malaysia	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Refining, Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Refining, Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
	Societal stability	Political stability and absence of violence/terrorism	Mining, Mt. Weld	Australia	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mining, Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mining, Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mineral processing, Mt. Weld	Australia	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Mineral processing, Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Mineral processing, Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Metallurgical extracting, Mt. Weld	Malaysia	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Metallurgical extracting Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Metallurgical extracting Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Refining, Mt. Weld	Malaysia	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Refining, Bayan Obo	China	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
			Refining, Mt. Pass	USA	(World Bank, 2016)		2015	1.75	Fair	1	2	2	1
Environment	Environmental regulatory requirement	Environmental regulations and standards	Mining, Mt. Weld	Australia	(Lynas, 2016)		2015	1.00	High	1	1	1	1
			Mining, Bayan Obo	China	-			5.00	Poor	5	5	5	5
			Mining, Mt. Pass	USA	(Chevron, 1998)		2014	4.13	Poor	3	4	1	5
			Mineral processing, Mt. Weld	Australia	(Lynas, 2016)		2015	1.00	High	1	1	1	1
			Mineral processing, Bayan Obo	China	-			5.00	Poor	5	5	5	5
			Mineral processing, Mt. Pass	USA	(Chevron, 1998)		2014	4.13	Poor	3	4	1	5
			Metallurgical extracting, Mt. Weld	Malaysia	(Lynas, 2016)		2015	1.00	High	1	1	1	1

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Refererence year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Metallurgical extracting Bayan Obo	China	-			5.00	Poor	5	5	5	5
			Metallurgical extracting Mt. Pass	USA	(Chevron, 1998)		2014	4.13	Poor	3	4	1	5
			Refining, Mt. Weld	Malaysia	(Lynas, 2016)		2015	1.00	High	1	1	1	1
			Refining, Bayan Obo	China	-			5.00	Poor	5	5	5	5
			Refining, Mt. Pass	USA	(Chevron, 1998)		2014	4.13	Poor	3	4	1	5
	Total environmental impacts	ReCiPe: Ecosystem and Human health	Mining, Mt. Weld	Australia	-			0	NAV				
			Mining, Bayan Obo	China	(Wolfensberger, 2015)	Value accounts also for mineral processing	2015	1.75	Fair	2	1	2	1
			Mining, Mt. Pass	USA	-			0	NAV				
			Mineral processing, Mt. Weld	Australia	-			0	NAV				
			Mineral processing, Bayan Obo	China	(Wolfensberger, 2015)	Value accounts also for mining	2015	1.75	Fair	2	1	2	1
			Mineral processing, Mt. Pass	USA	-			0	NAV				
			Metallurgical extracting, Mt. Weld	Malaysia	-			0	NAV				
			Metallurgical extracting Bayan Obo	China	(Wolfensberger, 2015)	Value accounts also for refining	2015	1.75	Fair	2	1	2	1
			Metallurgical extracting Mt. Pass	USA	-			0	NAV				
			Refining, Mt. Weld	Malaysia	-			0	NAV				
			Refining, Bayan Obo	China	(Wolfensberger, 2015)	Value accounts also for metallurgical extraction	2015	1.75	Fair	2	1	2	1
			Refining, Mt. Pass	USA	-			0	NAV				

G.11 Framework application, results and discussion: detailed data quality ranking of mining deposits in the anthroposphere

Figure 32 Results from Data Quality ranking from quantifying MDA (mining deposits in the anthroposphere) along the operational steps. R stands for reliability, Co for Completeness, GC for Geographical Correlation and TeC for Temporal Correlation.

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
Geological knowledge	Quantity	Mass	Collecting, Switzerland	Switzerland	own calculation		2014	1.75	Fair	2	1	1	2
			Manual processing, Switzerland	Switzerland	own calculation		2014	1.75	Fair	2	1	1	2
			Mechanical processing, Switzerland	Switzerland	own calculation		2014	1.75	Fair	2	1	1	2
			Metallurgical extracting, manual processing, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Metallurgical extracting, shredded, Switzerland	Switzerland	(Böni, 2015)		2016	0	NAV				
			Metallurgical extracting manual processing, Japan	Japan	own calculation		2005	3.88	Poor	3	1	2	5
			Metallurgical extracting shredded, Japan	Japan	own calculation		2005	3.88	Poor	3	1	2	5
			Metallurgical extracting manual processing, Germany	Germany	own calculation		2005	3.88	Poor	3	1	2	5
			Metallurgical extracting shredded, Germany	Germany	own calculation		2005	3.88	Poor	3	1	2	5
			Metallurgical extracting manual processing, Austria	Austria	own calculation		2005	3.88	Poor	3	1	2	5
			Metallurgical extracting shredded, Austria	Austria	own calculation		2005	3.88	Poor	3	1	2	5
			Metallurgical extracting manual processing, Vietnam	Vietna	own calculation		2005	3.88	Poor	3	1	2	5

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
				m									
			Metallurgical extracting shredded, Vietnam	Vietnam	own calculation		2005	3.88	Poor	3	1	2	5
			Refining, manual processing, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Refining, mechanical processing, Switzerland	Switzerland	(Böni, 2015)		2016	0	NAV				
			Refining manual processing, Japan	Japan	own calculation		2005	3.88	Poor	3	1	2	5
			Refining mechanical processing, Japan	Japan	own calculation		2005	3.88	Poor	3	1	2	5
			Refining manual processing, Germany	Germany	own calculation		2005	3.88	Poor	3	1	2	5
			Refining mechanical processing, Germany	Germany	own calculation		2005	3.88	Poor	3	1	2	5
			Refining manual processing, Austria	Austria	own calculation		2005	3.88	Poor	3	1	2	5
			Refining mechanical processing, Austria	Austria	own calculation		2005	3.88	Poor	3	1	2	5
			Refining manual processing, Vietnam	Vietnam	own calculation		2005	3.88	Poor	3	1	2	5
			Refining mechanical processing, Vietnam	Vietnam	own calculation		2005	3.88	Poor	3	1	2	5
	Quality	Mass fraction	Collecting, Switzerland	Switzerland	own calculation		2014	1.88	Fair	2	1	2	2
			Manual processing and mechanical processing, Switzerland	Switzerland	own calculation		2014	1.88	Fair	2	1	2	2
			Metallurgical extracting, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Metallurgical extracting, Japan	Japan	(Simoni et al., 2015; Wolfensberger et al., 2015)		2005	3.88	Poor	2	2	2	5
			Metallurgical extracting, Germany	Germany	(Simoni et al., 2015; Wolfensberger et al., 2015)		2005	3.88	Poor	2	2	2	5

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Metallurgical extracting, Austria	Austria	(Simoni et al., 2015; Wolfensberger et al., 2015)		2005	3.88	Poor	2	2	2	5
			Metallurgical extracting, Vietnam	Vietnam	(Simoni et al., 2015; Wolfensberger et al., 2015)		2005	3.88	Poor	2	2	2	5
			Refining, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Refining , Japan	Japan	(USGS, 2016)		2005	3.88	Poor	2	2	2	5
			Refining , Germany	Germany	(USGS, 2016)		2005	3.88	Poor	2	2	2	5
			Refining , Austria	Austria	(USGS, 2016)		2005	3.88	Poor	2	2	2	5
			Refining , Japan	Vietnam	(USGS, 2016)		2005	3.88	Poor	2	2	2	5
Eligibility	Ownership	Market concentration	Collecting, Switzerland	Switzerland	(Swico Abgabestellen, 2017)		2017	1.63	Fair	1	1	2	1
			Manual processing and mechanical processing, Switzerland	Switzerland	(Swico, 2017)		2017	1.63	Fair	1	1	2	1
			Metallurgical extracting, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Metallurgical extracting, Japan	Japan	(Bunge, 2015)		2015	0	NAV				
			Metallurgical extracting, Germany	Germany	(Bunge, 2015)		2015	0	NAV				
			Metallurgical extracting, Austria	Austria	(Bunge, 2015)		2015	0	NAV				
			Metallurgical extracting, Vietnam	Vietnam	(Bunge, 2015)		2016	0	NAV				
			Refining, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Refining, Japan	Japan	(Bunge, 2015)		2015	0	NAV				
			Refining, Germany	Ger-	(Bunge,		2015	0	NAV				

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
				many	2015)								
			Refining, Austria	Austria	(Bunge, 2015)		2015	0	NAV				
			Refining, Vietnam	Vietnam	(Bunge, 2015)		2015	0	NAV				
	Regulatory requirement	Operating license	Collecting, Switzerland	Switzerland	(Böni, 2015)		2015	1.00	High	1	1	1	1
			Manual processing and mechanical processing, Switzerland	Switzerland	(Böni, 2015)		2015	1.00	High	1	1	1	1
			Metallurgical extracting, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Metallurgical extracting, Japan	Japan	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
			Metallurgical extracting, Germany	Germany	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
			Metallurgical extracting, Austria	Austria	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
			Metallurgical extracting, Vietnam	Vietnam	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
			Refining, Switzerland	Switzerland	(Böni, 2015)		2015	0	NAV				
			Refining, Japan	Japan	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
			Refining, Germany	Germany	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
			Refining, Austria	Austria	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
			Refining, Vietnam	Vietnam	(Bunge, 2015)		2015	1.75	Fair	2	2	1	1
Technology	Machine and infrastructure knowledge	Machine and infrastructure knowledge	Collecting, Switzerland	Switzerland	(Böni, 2015)		2015	1.63	Fair	2	1	1	1
			Manual processing and mechanical processing, Switzerland	Swit-zer-	(Böni, 2015)		2015	1.63	Fair	2	1	1	1

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
				land									
			Metallurgical extracting, Switzerland	Switzerland	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Metallurgical extracting, Japan	Japan	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Metallurgical extracting, Germany	Germany	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Metallurgical extracting, Austria	Austria	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Metallurgical extracting, Vietnam	Vietnam	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Refining, Switzerland	Switzerland	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Refining, Japan	Japan	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Refining, Germany	Germany	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Refining, Austria	Austria	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
			Refining, Vietnam	Vietnam	(Bunge, 2015)		2015	3.00	Fair	4	2	1	1
	Machine and infrastructure use	Annual rate of collection, mining recovery and processing recovery	Collecting, Switzerland	Switzerland	Own calculation		2013	2.63	Fair	3	2	1	3
			Manual processing	Switzerland	Own calculation		2014	2.50	Fair	3	2	1	2
			Mechanical processing	Switzerland	Own calculation		2014	2.50	Fair	3	2	1	2
			Metallurgical extracting, manual, Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Metallurgical extracting, mechanical (mechanical processing), Switzerland	Switzerland	(Bunge, 2015)			0	NAV				

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Metallurgical extracting, Japan	Japan	Own calculation		2005	3.88	Poor	3	2	1	5
			Metallurgical extracting, Germany	Germany	Own calculation		2013	2.63	Fair	3	2	1	3
			Metallurgical extracting, Austria	Austria	Own calculation		2013	2.63	Fair	3	2	1	3
			Metallurgical extracting, Vietnam	Vietnam	Own calculation		2013	2.63	Fair	3	2	1	3
			Refining, manual, Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Refining, mechanical (mechanical processing), Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Refining, Japan	Japan	Own calculation		2005	3.88	Poor	3	2	1	5
			Refining, Germany	Germany	Own calculation		2013	2.63	Fair	3	2	1	3
			Refining, Austria	Austria	Own calculation		2013	2.63	Fair	3	2	1	3
			Refining, Vietnam	Vietnam	Own calculation		2013	2.63	Fair	3	2	1	3
	Costs to a country for collecting, mining and processing	Costs to a country	Collecting, Switzerland	Switzerland	Own calculation		2015	1.63	Fair	1	2	1	1
			Manual processing and mechanical processing, costs	Switzerland	Own calculation		2014	2.00	Fair	2	2	2	2
			Mechanical processing costs	Switzerland	Own calculation		2014	2.00	Fair	2	2	2	2
			Metallurgical extracting, manual, Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Metallurgical extracting, mechanical (mechanical processing), Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Metallurgical extracting, Japan	Japan	'-			0	NAV				

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Metallurgical extracting, Germany	Germany	'-			0	NAV				
			Metallurgical extracting, Austria	Austria	'-			0	NAV				
			Metallurgical extracting, Vietnam	Vietnam	'-			0	NAV				
			Refining, manual, Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Refining, mechanical (mechanical processing), Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Refining, Japan	Japan	Own calculation	proxy used for other location	2014	2.75	Fair	3	2	3	2
			Refining, Germany	Germany	Own calculation		2014	2.63	Fair	3	2	2	2
			Refining, Austria	Austria	Own calculation		2014	2.63	Fair	3	2	2	2
			Refining, Vietnam	Vietnam	Own calculation	proxy used for other location	2014	2.75	Fair	3	2	3	2
	Cost volatility for collecting, mining and processing	Cost volatility to a country	Collecting, Switzerland	Switzerland	Own calculation		2015	3.00	Fair	2	4	1	1
			Manual processing, costs	Switzerland	Own calculation		2014	2.00	Fair	2	2	2	2
			Mechanical processing, costs	Switzerland	Own calculation		2014	2.00	Fair	2	2	2	2
			Metallurgical extracting, manual, Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Metallurgical extracting, mechanical (shredding), Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Metallurgical extracting, Japan	Japan	'-			0	NAV				
			Metallurgical extracting, Germany	Germany	'-			0	NAV				

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Metallurgical extracting, Austria	Austria	'-			0	NAV				
			Metallurgical extracting, Vietnam	Vietnam	'-			0	NAV				
			Refining, manual, Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Refining, mechanical (shredding), Switzerland	Switzerland	(Bunge, 2015)			0	NAV				
			Refining, Japan	Japan	Own Calculation	proxy used for other location	2014	2.75	Fair	3	2	3	2
			Refining, Germany	Germany	Own Calculation		2014	2.63	Fair	3	2	2	2
			Refining, Austria	Austria	Own Calculation		2014	2.63	Fair	3	2	2	2
			Refining, Vietnam	Vietnam	Own Calculation	proxy used for other location	2014	2.75	Fair	3	2	3	2
Soicety	Human rights implications	Freedom of speech	Collecting, Switzerland	Switzerland	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Manual and mechanical processing, Switzerland	Switzerland	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Switzerland	Switzerland	0			0	NAV				
			Metallurgical extracting, Japan	Japan	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Germany	Germany	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Austria	Austria	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Austria	Vietnam	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
			Refining, Switzerland	Switzerland	-			0	NAV				
			Refining, Japan	Japan	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Refining, Germany	Germany	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Refining, Austria	Austria	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Refining, Vietnam	Vietnam	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
	Societal stability	Political stability and absence of violence/terrorism	Collecting, Switzerland	Switzerland	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Manual and mechanical processing, Switzerland	Switzerland	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Switzerland	Switzerland	0			0	NAV				
			Metallurgical extracting, Japan	Japan	(World Bank, 2016)	proxy used for other location	2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Germany	Germany	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Austria	Austria	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Metallurgical extracting, Vietnam	Vietnam	(World Bank, 2016)	proxy used for other location	2015	2.38	Fair	2	1	3	1
			Refining, Switzerland	Switzerland	-			0	NAV				
			Refining, Japan	Japan	(World Bank,	proxy used for other location	2015	2.38	Fair	2	1	3	1

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
					2016)								
			Refining, Germany	Germany	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
Environment			Refining, Austria	Austria	(World Bank, 2016)		2015	1.63	Fair	2	1	1	1
			Refining, Vietnam	Vietnam	(World Bank, 2016)	proxy used for other location	2015	2.38	Fair	2	1	3	1
	Environmental regulatory requirement	Environmental regulations and standards	Collecting, Switzerland	Switzerland	(Cenelec 50625-2, 2015)		2015	1.00	High	1	1	1	1
			Manual and mechanical processing, Switzerland	Switzerland	(Cenelec 50625-2, 2015)		2015	1.00	High	1	1	1	1
			Metallurgical extracting, Switzerland	Switzerland	0		2015	1.00	High	1	1	1	1
			Metallurgical extracting, Japan	Japan	(Hitachi, 2017)		2017	3.00	Fair	4	1	1	2
			Metallurgical extracting, Germany	Germany	(Loser Chemie, 2017)		2017	1.63	Fair	1	1	1	2
			Metallurgical extracting, Austria	Austria	(Chevron, 1998)		1998	1.63	Fair	1	1	1	2
			Metallurgical extracting, Vietnam	Vietnam	-	No information publically available		5.00	Poor	5	5	5	5
			Refining, Switzerland	Switzerland	-		2015	1.00	High	1	1	1	1
			Refining, Japan	Japan	(Hitachi, 2017)		2016	3.00	Fair	4	1	1	2
			Refining, Germany	Germany	(Loser Chemie, 2017)		2016	1.63	Fair	1	1	1	2
			Refining, Austria	Austria	(Chevron, 1998)		1998	1.63	Fair	1	1	1	2
			Refining, Vietnam	Vietna	-	No information publi-		5.00	Poor	5	5	5	5

Component	Sub-component	Indicator	Name of data set	Location	Reference	Remark	Reference year	DQR Score	Descriptor of data quality	R Score	Co Score	GC Score	TeC Score
				m		cally available							
	Total environmental impacts	ReCiPe: Ecosystem and Human health	Collecting, Switzerland	Switzerland	(Wolfensberger, 2015)		2015	1.00	High	1	1	1	1
			Manual processing, Switzerland	Switzerland	(Wolfensberger, 2015)		2015	1.00	High	1	1	1	1
			Mechanical processing, Switzerland	Switzerland	(Wolfensberger, 2015)		2015	1.00	High	1	1	1	1
			Metallurgical extracting, manual, Switzerland	Switzerland	-		2015	1.00	High	1	1	1	1
			Metallurgical extracting, mechanical (shredding), Switzerland	Switzerland	-			0	NAV				
			Metallurgical extracting, Japan	Japan	-			0	NAV				
			Metallurgical extracting, Germany	Germany	-			0	NAV				
			Metallurgical extracting, Austria	Austria	-			0	NAV				
			Metallurgical extracting, Vietnam	Vietnam	-			0	NAV				
			Refining, manual, Switzerland	Switzerland	-		2015	1.00	High	1	1	1	1
			Refining, mechanical (shredding), Switzerland	Switzerland	-			0	NAV				
			Refining, Japan	Japan	-			0	NAV				
			Refining, Germany	Germany	-			0	NAV				
			Refining, Austria	Austria	-			0	NAV				
			Refining, Vietnam	Vietnam	-			0	NAV				

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Appendix H Accepted proposal for summer school from E-Waste Academy-Scientists Edition (EWAS) 2014

Accessing critical raw materials from e-waste – a geological exploration perspective

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Abstract

The global consumption of primary raw materials is increasing sharply and simultaneously with a loss of critical raw materials. To reduce these losses, their causes must be understood. The aim of this study is to explore a potentially sustainable access route to critical materials in WEEE in order to gain potential new insights into how to facilitate secondary material mining in an effective way. The first step of primary raw material deposit discovery (the exploration process) was critically analysed. A reconnaissance exploration of two secondary materials was also conducted. The results demonstrate that secondary material deposits of critical raw materials have higher mass fractions than a mined primary raw material deposit. The study indicated that the extraction of secondary materials is likely to become energetically, economically and environmentally more viable.

1 Introduction

The production of electrical and electronic equipment (EEE) is booming in modern society [1]. The increasingly wide range of EEE on the market combined with short lifetimes caused by changes in fashion and in-built rapid obsolescence has led to significantly increased formation of waste electronic and electric equipment (WEEE). Sites where WEEE is collected may be regarded as potential urban deposits of raw materials. In contrast, ore deposits are the prolonged formations of local environmental and geodynamic settings [2].Once these geological heritages of accumulated raw materials are consumed, they are irreplaceable in any period significant to human beings. Additionally, the ore grade from primary raw materials[37] is decreasing [3]. However, raw material extraction from primary raw material deposits has steadily increased since 2000 [4] and more products are entering the market. Once these products reach their end-of-life, it is vital to facilitate the recovery of raw materials from them. At present, one of the most prominent geological heritages is Rare Earth Elements (REE) [5], because their properties can currently not be substituted by alternative metals. Additionally, less than 1% of the used REE can be recycled [6]. Thus, today these secondary materials[38] follow a nearly linear material flow, from design to landfill disposal instead of a desired circular material flow [8].

To facilitate a circular material flow, it is vital to understand how to access raw materials in products like WEEE in a cost-effective and efficient way [9], [10], [11]. Therefore, a knowledge base on secondary material recovery needs to be developed. In a first approach we made the assumption that a primary raw material is accessible if a systematic evaluation process has shown that a mine can be developed. In primary raw material mining, the first step is the deposit discovery, i.e. exploration process [12], [13]. Brunner [9] emphasised that similar to primary raw material mining, comprehensive information about a scientific and structured mining approach is needed in secondary material mining. This encompasses knowledge of the mining site and material, abundance, economics and technology, including impacts on mining on environment and society [10], [14]. The aim of this study was to explore a potentially sustainable access route to critical materials in WEEE in order to gain potential new insights into how to facilitate secondary material mining in an effective way. Therefore, from primary raw material mining, the exploration process is critically analysed. We then focus on the first stage of the exploration process: the reconnaissance exploration. Finally, we examine the secondary material perspective via two examples of critical REE materials in order to highlight how this information could potentially support access to secondary materials.

2 Exploring the access of critical raw material from e-waste

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[37] Primary raw materials are materials extracted from the geosphere [7].

[38] Secondary materials are materials sourced from recycling [7].

2.1 Primary raw material exploration

2.1.1 Exploration process

In primary raw material mining, the first process in a search for a deposit is the exploration stage [12] (Figure 1). This resource assessment evaluates the mine viability [13] such that the raw material will become accessible. Since the exploration process can take 1-3 years and involves high investments [10], a geologist must follow a scientific and systematic procedure that increases access to likely viable mine development projects [15]. This also includes the monitoring, reporting and evaluating of the impacts on environment and society from the beginning. It is vital to commence these impact studies as early as possible, in order to avoid unexpected costs [12], [16]. Haines et al. [14] highlight that for sustainable mining the integration of external benefits and costs of impacts have to be a prerequisite. Thereby sustainability understanding needs to distinguish between ecological, economic, social, technological, and governance aspects [17], [18].

The curve shown in Figure 1 indicates the average number of prospects[39] [15] that are generated from the beginning until the end of the exploration process. It clearly shows that most projects do not pass the first phase. In the second phase (detailed exploration), exact modelling (respective micro level investigation [19]) of the parts of the prospected area are carried out. This involves extensive and systematic data collection and detailed understanding of the geological processes, e.g. quantitative resource assessment [20] and its modelling of impacts on society and environment [14]. During the last phase, the intention is to make a final decision with respect to mine development through evaluating the comprehensive data and understanding of a potential deposit [12]. Thereby, it is vital to consider if society, infrastructure, technology, governance and economy promote or prevent access to the intended mine development, [12], [13], [21]. To enable coherent and correct use of terminology, the resource assessment is based on international classification standards [13].

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[39] The prospect is a restricted volume of ground that is considered to have the possibility of directly hosting an ore body and is usually a named geographical location [15].

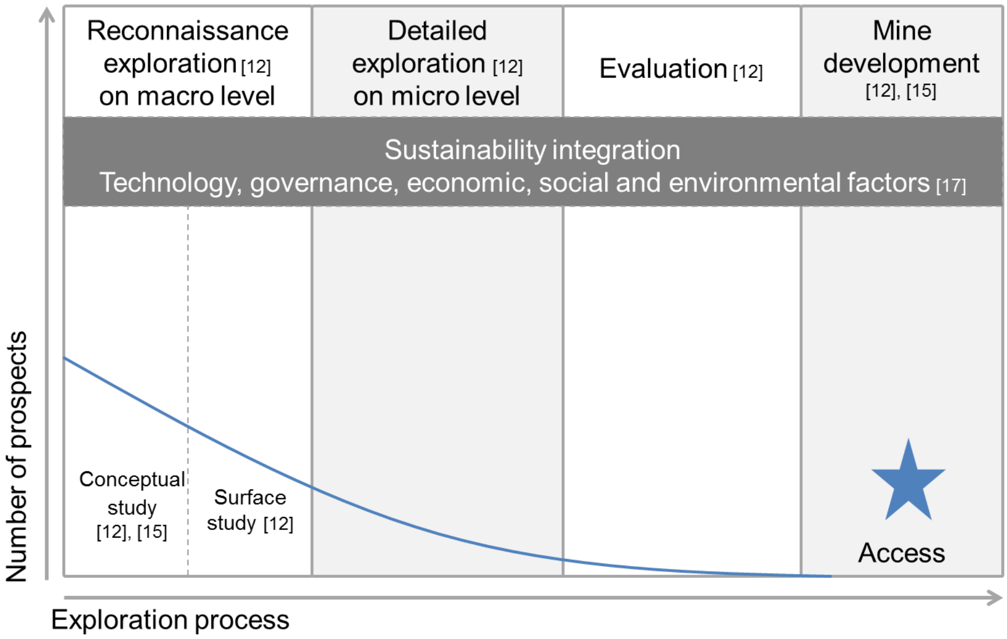

Figure 1. Exploration process steps towards the identification of accessible primary raw materials as described by Marjoribanks [15].

2.1.2 Reconnaissance exploration

In this phase, a macro investigation is carried out. This encompasses collection, modelling and interpretation of existing geological knowledge and maps [12]. The generation of new prospects is a critical stage and involves earth surface observations for indications of mineralisation and initial drillings to identify the target [15]. Additionally, first information on influences on society and environment are collected, [14], [17]. The results provide an approximate understanding of the potential resource [19] as a preparation for a detailed exploration.

2.2 Secondary material reconnaissance exploration

Similar to primary raw material mining, it is vital to carry out a desk study first from a predefined location and raw material i.e. a material flow assessment [22] and a description of the geological location and its included materials [23].

2.2.1 Two case application of secondary material reconnaissance exploration of a potential deposit in Switzerland

We describe the reconnaissance exploration of two REE End-of-life applications that have no substitute [25] and their recovery is still under development for Switzerland [24]. These potential deposits occur in different local environments. The first case application, Neodymium (Nd) is built into Neodymium-Iron-Boron permanent magnets within electrical cars, which are mobile during their use and at their end-of-life they are collected by recyclers at a fixed location for depollution and dismantling.

The second case application, Europium (Eu), is applied as an oxide within fluorescent lamps that are fixed during use and also collected by recyclers for processing. To enable a comparison between primary and secondary materials, we have compared these secondary materials with a primary raw material mine, the Mount Weld deposit in Australia [23]. This reconnaissance exploration has demonstrated quantities and mass fractions of secondary materials that shall be pursued further within a detailed exploration (Table 1). In particular, the macro-level calculation revealed higher mass fractions from the secondary material deposits than the primary raw material mine. For Eu the minable quantity, from the fluorescent powder, is only four times smaller compared to the primary raw material mine over the same mine period.

Table 1. Summary of primary and secondary material deposits finding from the reconnaissance exploration.

Description criteria	*Mt. Weld, Australia*	*Raw Material: Neodymium-Iron-Boron permanent magnet case study*	*Raw Material: Europium (Eu) fluorescent powder case study*
Deposit description [26]	Mined deposit with REE	Deposit is identified at recycler of electrical car with Neodymium-Iron-Boron permanent magnet	Deposit is identified at recycler of fluorescent lamps with Eu fluorescent powder
Location of deposit [26]	A steeply plunging cylindrical carbonatite complex enclosing REE, which intrudes the central part of the linear graben-like zone [23].	>70 car recycling sites. The number of recycling business is increased in urban areas. They sort the auto parts into spare parts and scrap [28].	Four recyclers under contract by an independent Swiss Light Recycling Foundation: SLRS [27].
Prospect & its grade [26]	The central lanthanide deposit contains in the carbonatite complex (9.88 Mt @ 10.7weight-% rare earth oxides (REO), 0.85weight-% Nd, 0.02weight-% Eu, 0.001weight-% Er). Very high-grade concen-	By 2030, the Neodymium-Iron-Boron permanent magnet deposit is expected to contain $Nd_2Fe_{14}B$ 2,691t @ 27weight-% Nd and 15,143td @ 27weight-% Nd by 2050 [29]. The amount of magnet de-	The distilled fluorescent powder includes Eu as Eu_2O_3 but also the REE: yttrium, lanthanum, cerium, gadolinium, terbium and mercury. In 2011, this deposit contained 22,287t @ 0.6weight-% Eu [24]. In 2030, it is ex-

Description criteria	*Mt. Weld, Australia*	*Raw Material: Neodymium-Iron-Boron permanent magnet case study*	*Raw Material: Europium (Eu) fluorescent powder case study*
	trations of REO in the regolith result from secondary monazite in polycrystalline aggregates [23].	pends strongly on the application of the motor.	pected to contain 76,420t @ 0.6weight-%.

3 Conclusion and Outlook

Overall, this study has demonstrated that the secondary resource sector could gain from applying a geological perspective to secondary material mining. The mass fraction from the secondary materials deposits was revealed to be higher than the mass fraction from the primary raw material deposit. For Eu it is evident that the minable quantity from the fluorescent powder is only four times smaller compared to the primary raw material mine over the same mine period. Consequently, this deposit assessment shall be continued further within a detailed exploration. The results of this study highlights that extraction, respectively accessing critical material from secondary materials, is likely to become energetically, economically and environmentally more viable in the near future.

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Appendix I Accepted proposal for proceedings of International Workshop on Technospheric Mining

MINING FROM ANTHROPOGENIC DEPOSITS: DEVELOPING THE FOUNDATIONS TO EVALUATE THE ACCESSIBILITY OF RARE EARTH METALS FROM END OF LIFE PRODUCTS

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Introduction

An increased number of geochemically scarce metals[45] are entering our daily lives via new technological applications (Zepf *et al*., 2014). A reversal of this trend is not foreseeable, leading to concerns about security of supply. Today's raw material situation is considered critical for many of these scarce metals because: (i) the production of raw material is concentrated to a few countries (Simoni *et al.*, 2014), (ii) there are limited options for substitutions (Graedel *et al.*, 2013), and (iii) recycling rates for these metals are very low (UNEP, 2012). In order to close material cycles and with this potentially ease the supply situation, raw material management requires to be rethought (Ongondo *et al.*, 2015). One approach is being implemented by the Swiss ordinance on the return, take-back and disposal of electrical and electronic equipment (ORDEE), which is currently being revised. The future ORDEE will require recovery of scarce metals from technological equipment where possible. This will not only apply for waste electrical and electronic equipment (WEEE) but also for electrical and electronic equipment from buildings and vehicles, provided that this is possible with proportional effort (FOEN, 2013).

How can this be tackled?

Prerequisites for the recovery of raw materials are its occurrence, i.e. its "availability", and its "accessibility". Whilst the notion of "availability" is typically well-understood, an explicit and systematic scientific examination of the concept of "accessibility" has not yet been provided. Implicitly, individual aspects of raw materials accessibility have been included in studies of economic geology, for instance within different resource classification frameworks (Weber, 2013). A first implementation of such implicit aspects in anthropogenic deposits was conducted by Mueller *et al*. (2015). They developed a framework that allows the establishment of analogies between geological and anthropogenic processes, and applied this framework to three products containing rare earth elements (REE), aimed at identifying the most concentrated deposits in the anthropogenic cycle.

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[45] Geochemically scarce metals are those metals, whose crustal abundance is <0.01 weight-% (Wäger *et al.,* 2012).

Based on these implicit applications, the following research questions can be derived: How can "accessibility" be conceptualised in the context of geogenic mining approaches? How can these concepts of "accessibility" be transferred to anthropogenic deposits under explicit considerations of the requirements for a more sustainable raw material mining? How accessible are anthropogenic raw materials?

What is the PhD research addressing?

This PhD research aims to elucidate and apply the concept of accessibility to raw materials from anthropogenic deposits. Thereby, particular attention will be paid to the requirements of sustainable raw material mining. The study will involve the following steps:

1. Elucidation of the term "accessibility" and its use in the context of geogenic and anthropogenic deposit discovery.
2. Identification, selection and weighting of key factors that influence the accessibility of both geological and anthropogenic raw materials under consideration of sustainability constraints.
3. Modelling and evaluation of the accessibility of REE in anthropogenic deposits based on the developed framework. This will be applied onto electrical and electronic equipment in buildings and vehicles.

What has been addressed so far?

The first research step has been tackled. This was split into two separate analyses; first, the elucidation of the term "accessibility" by extracting semantic relevant data; secondly, analysing the use of "accessibility" in the context of geogenic deposit discovery.

For the first analysis, a generic applicable definition for the geological and anthropogenic context was derived from the dictionaries Oxford, Cambridge and the lexical database WordNet. Following, "accessibility" can be described by synsets[46] "availability" and "approachability" (WordNet, 2014). On this basis, the extraction of semantic relevant data was conducted. This included a structural, statistical and semantical analysis as suggested by Weinhofer (2010). Therefore, 161 papers and books from geogenic and anthropogenic deposit discovery literature were studied with the PDF-XChange Viewer software (2014). This analysis of "accessibility", "availability" and "approachability" resulted in the following. The term "approachability" was not used in this context. Both terms "accessibility" and "availability" are almost not used in the heading, but in the body of the text within diverse contexts, such as geology, waste management, technology, infrastructure, society, environment, governance and economy. This extraction showed concurrence with the generic definition. This first research step was concluded with the development of our own definitions to direct future research. The working definitions comprise: **available / availability**: "exists" in the geosphere and/or anthroposphere at "relevant"[47] mass fractions; **approachable / approachability**: it is possible to get to the material of interest but it is unknown if the material actually exists at "relevant" mass; and **accessible / accessibility**: there are no "major"/"significant" constraints (e.g. ownership, protected areas, ...) to "access" / "get to" the material of interest in view of potentially extracting it.

For the second analysis, approaches from geological deposit discovery were critically analysed. These approaches were then transferred based on existing similar research; and further developed to evaluate the development of both the geogenic and anthropogenic deposit discovery. This was complemented through discussions with experts. On this basis, the understanding of "accessibility" to

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[46] Sets of cognitive synonyms (WordNet, 2014).

[47] Raw material estimated with a high level of confidence and hardly any obstacle will prevent its exploitation (Pohl, 2011).

raw material was positioned at an early stage of the classification / evaluation steps of the deposit discovery approaches. This "accessibility" positioning enables a prospective early stage comparison for mining projects. This research was concluded with the development of a conceptual framework to guide future research on quantifying the degree of accessibility (Figure 1). This framework comprises of three key stages: first, sustainability constraints, which provide the basis for the stages; second, classification / evaluation steps; and third, key influencing factors. Currently, sustainability is not integrated consistently within the classification / evaluation steps. Therefore, we propose to restrictions through sustainability constraints through the entire quantification of accessibility. For a broad sustainability integration, we suggest to integrate the domains from the mineral resource landscape perspective: technology, governance, environment, society and economy (Giurco and Cooper, 2012). The second stage comprises the classification / evaluation steps. These pose a successive description for the final decision on mine development. Consequently, they are the systemic structure towards deciding on mine development. The classification / evaluation steps encompass three successive main steps: 1. "reconnaissance exploration", 2. "detailed follow-up exploration" and 3. "final evaluation". The "reconnaissance exploration" is a macro-level evaluation that aims to sort out promising "prospects[48]" rapidly with low costs. The "detailed follow-up exploration" is a micro level evaluation that concludes with a prefeasibility study.

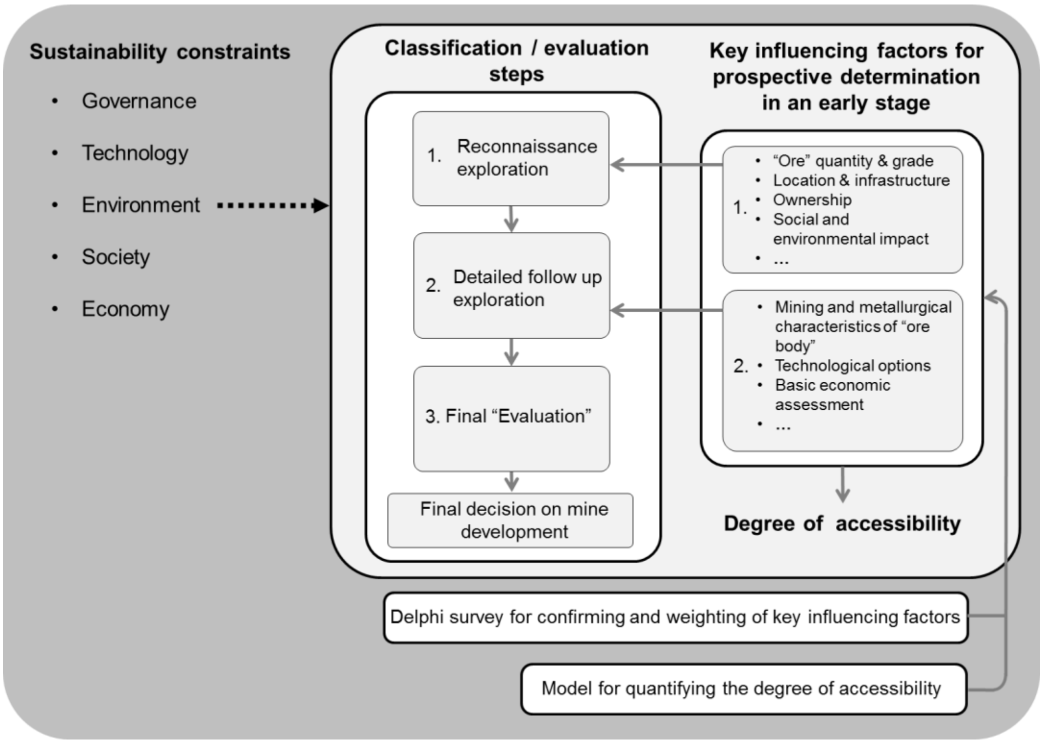

Figure 1. Approach to quantify the degree of accessibility of geogenic and anthropogenic raw materials.

The last step, i.e. final "evaluation", aims to generate comprehensive data from the "prospect" to determine the final decision on mine development and satisfy investors. This step is concluded with a feasibility study. The feasibility study is summarised by classifying the final decision in e.g. a resource classification framework. Within the classification / evaluation steps, each sequential step is influenced by different key influencing factors. In geology they are known as modifying factors or quantifying elements. Some of these key influencing factors affect the final result more than others. At pre-

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[48] Prospect is a distinct volume of ground that is considered to have the possibility of directly hosting an "ore body" and is usually a named geographical location (Marjoribanks, 2010).

sent, it is unclear which of these factors the most important ones are and how strongly they influence the “degree of accessibility”. By understanding the effects from selected key influencing factors at an early stage, a prospective statement on the degree of accessibility of raw materials can be derived. This applies for both geogenic and anthropogenic deposit discovery. On this basis, a foundation for establishing a common platform between geogenic and anthropogenic deposit discovery is provided. Importantly, a prospective statement on the recovery of scarce metals with a proportional effort can be formulated, which quantification is required according to the future ORDEE.

What are the next research steps?

The identified factors that influence the “accessibility” of raw materials will be confirmed and weighted using a Delphi study with independent experts. On this basis, a model will be developed and simulation experiments will be carried out to quantify the degree of accessibility of REE in buildings and vehicles.

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