



Development of a new resource consumption impact assessment indicator : applied to extraction of materials versus recycling.

Naeem Adibi

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Naeem Adibi. Development of a new resource consumption impact assessment indicator : applied to extraction of materials versus recycling.. Civil Engineering. Ecole Centrale de Lille, 2016. English. NNT : 2016ECLI0013 . tel-01488037

HAL Id: tel-01488037

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N° d'ordre : 306

CENTRALE LILLE

Thèse

Présentée en vue d'obtenir le grade de Docteur en

Spécialité : Génie Civil

Par

Naeem ADIBI

DOCTORAT DELIVRE PAR CENTRALELILLE

Titre de la thèse :

**Développement d'un indicateur d'évaluation d'impacts de
la consommation des ressources : cas d'application à une
extraction des matériaux versus un recyclage**

Soutenue le 1^{er} Décembre 2016 devant le jury d'examen

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Ecole Doctorale SPI 072 (Lille I, Lille III, Artois, ULCO, UVHC, Centrale Lille)

Acknowledgements

I would like to express my deep gratitude to Professor Zoubeir LAFHAJ my research advisor and supervisor, for his incredible support, kind and patient guidance and useful critiques of this research work. I am very grateful for all of the things he has taught me (in research and personally). In particular, I should acknowledge Pr LAFHAJ self-control and ability to tolerate my moody and quick temper within the last four years!

I would like to thank deeply Doctor Jérôme PAYET my co-advisor, who provided knowledge, guidance, and support, especially when I faced tough and challenging scientific and technical issues. His willingness to give his time so generously has been very much appreciated. I appreciate his continuous encouraging comments and discussions.

My very deep gratitude to my director in cd2e, Christian TRAISNEL. His incredible support to me is unforgettable! His guidance, knowledge, and enthusiastic encouragement is a source of inspiration and self-confidence for me.

Further I would like to acknowledge the president of jury Pr. Mohamed AL-HUSSEIN and the members of jury Dr. Anne VENTURA, Pr. Guido SONNEMANN, Pr. Essaieb HAMDI and Christian TRAISNEL to honor me to participate and provide very useful hints for improving this thesis manuscript, which I have delightedly embraced.

Three chapters of current dissertation are my peer-reviewed articles (where in I was the first author) which are either published or under review (at the time of printing this dissertation chapter 1 and 2 is published article while chapters 3 and 4 are submitted and an extra article under drafting). Hence, I should acknowledge all the co-authors whose contribution and support undoubtedly helped me to finish my PhD research work successfully.

I would like to acknowledge the helps from my colleagues and friends in Ecole Centrale de Lille within the last few years who supported me in different ways. Special

thanks to Dr Faycal EL FGAIER, who provided technical support and personal encouragements with an extraordinary patience and calm.

My special thanks go to my colleagues in [avniR] platform, Dr Vanessa PASQUET, Aubin ROY and Alice SALAMON who provided a friendly environment in the office. Our non-stop discussion in the office helped me to change my mind while I was upset or disappointed! I would like also to acknowledge the helps from my colleagues and friends in cd2e within the last few years who supported me in different ways.

I would like to thank Dr. Mehdi KESHAVARZ HEDAYATI, Pedram MASOUDI and Mehdi MAHMOUDYSEPEHR who partly involved in the proof-reading and provided feedback and support on the drafting phase of this work.

And last not the least I wish to express my immense gratitude, appreciation and acknowledge the not-ending support of my Family, especially my Father Professor Aliasghar ADIBI, my mother Dr. Zainab FAGHIHI and my sister Zahra ADIBI. Their endless encouragements, support, patience is unforgettable.

Naeem ADIBI

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Date 01/12/2016

Résumé

L'augmentation de la consommation de ressources suscite des préoccupations quant à leur disponibilité. Ces dernières années, les organisations nationales et internationales ont défini l'approvisionnement durable des ressources et la mise en place d'une économie circulaire comme des objectifs centraux de leurs stratégies à court et long termes. Dans ce contexte, différentes approches méthodologiques relevant de l'Analyse du Cycle de Vie (ACV) sont utilisées pour caractériser l'impact de l'épuisement des ressources. Les approches actuelles fournissent néanmoins des visions partielles, car dépendantes de données disponibles limitées, et ne reflètent pas les défis de la société en lien avec cette question des ressources.

Un premier problème est le manque, pour certaines ressources, de facteurs de caractérisation ; ce qui rend l'interprétation des résultats d'ACV difficile et peut, dans certains cas, être trompeur. Par exemple, le risque de pénurie élevé des terres rares, qui sont une des matières premières les plus critiques, n'est pas pris en compte dans les méthodes actuelles d'évaluation d'impact du cycle de vie.

Une seconde préoccupation majeure réside dans le cadre conceptuel des méthodes existantes d'évaluation de l'impact sur les ressources de l'ACV. Les défis auxquels est confrontée la société, ne se reflètent pas complètement de façon cohérente dans ces méthodes. Cette thèse propose un cadre pour évaluer les méthodes existantes d'épuisement des ressources dans l'ACV. Sur la base de cette évaluation, des développements visant à compléter les méthodologies actuelles sont proposés, en y ajoutant des paramètres importants (exemple : la recyclabilité) qui ne sont pas encore couverts par les présentes méthodes d'évaluation de l'impact du cycle de vie.

Afin d'apporter une solution à la première préoccupation concernant les méthodes actuelles d'évaluation du cycle de vie des ressources, la thèse aborde pour la première fois, la question des facteurs de caractérisation manquants des terres rares. Pour surmonter ce problème, les modèles de calcul de l'impact des ressources de CML et ReCiPe sont utilisés comme référence. Le présent travail nous a permis de calculer les facteurs de caractérisation pour les 15 terres rares ; ces facteurs seront utiles pour les mises à jour des méthodes mentionnées précédemment et permettront in fine (via une mise en œuvre dans des logiciels d'ACV comme Simapro ou GaBi) de traiter de l'épuisement des ressources des terres rares.

Pour répondre à la seconde préoccupation, de nouveaux modèles de calcul des facteurs de caractérisation sont développés, prenant en compte différents critères influant sur la disponibilité des ressources à travers différents cycles de vie. L'indicateur ressource proposé dans cette thèse, le « Global Resource Indicator » intègre de nouveaux aspects

comme la recyclabilité et la criticité afin de mieux caractériser l'impact de la consommation de ressource.

Cette nouvelle méthode est capable d'évaluer tous les types de ressources, les renouvelables et les non renouvelables. Les résultats montrent que l'importance des différentes ressources est influencée par l'introduction de nouveaux indicateurs. La sensibilité des facteurs de caractérisation à l'égard de différents paramètres d'entrée est testée et discutée. Les résultats sont comparés avec la méthode CML et une analyse des différences est présentée.

Deux études de cas ont été menées durant ces travaux. La première est un essai de l'applicabilité des facteurs de caractérisation des terres rares issus des modèles CML et ReCiPe. L'application de ces facteurs dans l'ACV d'aimants au néodyme, a montré que la prise en compte des terres rares peut avoir un effet significatif sur l'impact ressource de l'ACV des produits. La seconde étude a permis de tester les nouveaux modèles de calcul des facteurs dans une étude de cas sur une éolienne. Enfin, l'applicabilité de ces facteurs est validée et des précautions d'utilisation sont fournies pour les futurs praticiens.

La méthode et les facteurs nouvellement développés fournissent une vision plus exhaustive de la disponibilité des ressources et peuvent être utilisés dans des analyses du cycle de vie ou dans des approches d'économie circulaire. Ce travail fut produit en partenariat avec le cd2e et le pôle de compétitivité Team². Il a également été réalisé en collaboration avec le bureau d'études et d'expertise en ACV, Cycleco.

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List of acronyms

CEN	European Committee for Standardization
CF	Characterization Factor
CML	Centrum voor Milieukunde Leiden
DG	Directorate-General
DG ENV	Directorate General for Environment
ELCD	European Life Cycle Database
EN	European Norm
EoL	End of Life
EPD	Environmental Product Declaration
EPLCA	European Platform on Life Cycle Assessment
FU	Functional Unit
GHG	Greenhouse Gas
ILCD	International Reference Life Cycle Data
ISO	International Organization for Standardization
JRC	Joint Research Center
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
REE	Rare Earth Element
REPA	Resource and Environmental Profile Analysis
SD	Sustainable Development
SETAC	Society of Environmental Toxicology and Chemistry
UNEP	United Nations Environment Programme

1. An introduction to Life Cycle Assessment and its application in the construction sector

Highlights:

- Introduction to the Life Cycle Assessment method is provided.
- Application of LCA in building and construction is highlighted.

1.1 Introduction

Life Cycle Assessment (LCA) is based on the principles of sustainable development. LCA as a tool aims to assess environmental impacts associated with all the stages of a product's life from cradle to grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). The effectiveness and efficiency of these methods lies within the fact that they take into account all life cycle stages of a product, from the extraction of raw materials to End-of-Life treatment through an assessment process, covering different impact categories such as climate change, human health, ecosystems and resources. Considering the stages of a product life cycle and different impact categories, LCA can be utilized as a decision-making tool to help innovating processes and avoid problem of shifting environmental impacts, also minimizing secondary effects. LCA methods have demonstrated their efficiency in systematic environmental assessment of a product, a service or a process [1].

In LCA, inputs and outputs as extracted resources and emissions from different stages of life cycle are assessed in terms of impacts called Life Cycle Impact Assessment (LCIA). Based on the principles of the Sustainable Development (SD), Life Cycle Assessment (LCA) contains a range of methods in assessing environmental, social¹[2] and economic aspects of specific products, processes and services.

The aim of this chapter first of all is to introduce the LCA method based on reliable references. Some insights are also provided on historical background and different theoretical developments. The chapter highlights the missing or contradictory aspects to be discussed and further developed in the successive chapters. It includes also an

¹ Social LCA is under development. The method intends to assess social implications or potential impacts.

introductory discussion on the use of LCA within the building and construction sector with a focus on resource efficiency in construction.

1.1.1 Theoretical evolution of LCA

The concept of LCA was developed in the United States, late 1960s and early 1970s [3]. At the same time, the other almost identical approach was developed in Europe. Minor public attention was given to LCA, and limited written documents are available between 1970 and 1990. However, the history of LCA is well documented Since 1990 [4].

The complexity of environmental issues is observed primarily by the scientific communities in the 1960s. In 1969, the pattern that later LCA is founded based on, was first applied by Harry Teasley, the Coca-Cola Company [3]. "Resource and Environmental Profile Analysis" (REPA), is a frequent terminology, has been used since 1970, for environmental life cycle-based approaches [3]. In the following years, similar "cradle to grave" approaches, related to environmental assessment of products is developed in France and other parts of Europe.

The LCA, as known today, was partly presented by SETAC (Society of Environmental Toxicology and Chemistry). In 1990, the first document, under the same name and methodology (general structure), was reported by SETAC [4]. In the following years, from 1990 to 1993, various aspects of LCA were further studied and organized by SETAC.

In Europe, Leiden University, the Netherlands (Centrum voor Milieukunde Leiden: CML) played an important role in early 90s to establish the roadmap of further research on LCA. The LCA methodology published in 1993 by CML was one of major foundations of LCA in Europe [5].

The leadership was resumed by ISO from 1994 to 2001, in order to follow the path toward a unified methodology for LCA. Four standards (ISO 14040-43) were issued by delegates from 24 countries, where 16 countries sent observers [6]. The critical review

and its importance in case of comparative assertion was introduced in ISO 14041 for the first time.

In France, the development of ISO 14040 fixed pragmatic basis, and it was decided to use the term "Life Cycle Assessment" (LCA). From 1997, actions steadily improved and the results have also become more reliable while their communication was more formal.

Cooperation between the United Nations Environment Programme (UNEP) and the SETAC was officially launched in 2002 [7], and engaged activities are followed until today. The major reason for this agreement was the requirement of UNEP to implement the sustainable development as the most important aim of humanity in the 21st century. Sustainability can be defined as the practice of maintaining processes of productivity indefinitely - natural or human made - by replacing resources used with resources of equal or greater value without degrading or endangering natural biotic systems [8]. Sustainability is not easy to be measured, but if a solution exists, that would be derived from life cycle thinking approaches based on LCA method.

Later, one of the major LCA events (2005), European Commission's "Joint Research Center" (JRC) together with its Directorate General for Environment (DG ENV), jointly established European Platform on Life Cycle Assessment (EPLCA). Among other deliverables, European Platform on LCA is coordinating and supporting the development of the International Reference Life Cycle Data System (ILCD).

The ILCD primarily gathered the series of ILCD handbooks and most recently launched Life Cycle Data Network. The ILCD is based on LCA current consensus best practices. It is developed by a broad consultation and is coordinated by European Commission to ensure the independence [9].

The most recent initiative called "Single Market for Green Products" was started by European Commission following the request of the Council to "develop a common methodology on the quantitative assessment of environmental impacts of products, throughout their life-cycle, in order to support the assessment and labelling of different

products”. A three year pilot [10], started in 2013, to check the feasibility of applying Product Environmental Footprint (PEF) method (published by European Commission) in variety of sectors.

1.1.2 Evolution of Standardization and Regulations of LCA

The new standard ISO 14044 (Environmental management - Life cycle assessment - Requirements and guidelines), in addition to a new revision of ISO 14040, in 2006 [11], replaced ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000. Publication of new international standards on life cycle assessment (ISO 14040 and ISO 14044) was done in 2006. It is recommended that new standards be used as the reference documents for LCA practitioners.

European Platform on LCA, developed by European Commission’s "Joint Research Center" (JRC) together with its Directorate General for Environment (DG ENV) realized research studies and provided numerous resources on LCA, including ILCD handbooks as major LCA reference documents. One of the most exhaustive handbooks, published by JRC called “General guide for Life Cycle Assessment - Detailed guidance” [12] is one of the mostly used LCA reference documents in Europe, these days.

To measure and communicate environmental footprint of products throughout their life cycle, in 2013 European Commission published the PEF/OEF method [13], and through a pilot phase, will test this method on different product groups for further potential policy making in LCA up to 2020.

In 2009, the North American Sustainability Consortium was founded by Jay Golden (ASU) and Jon Johnson (University of Arkansas), and continues to be jointly administered by the two universities today. More than 75 member companies participated in 2011 in the Consortium. The goal to develop the Consortium is to work collaboratively to build a scientific foundation that drives innovation to improve consuming product

sustainability. The Transparency of methodologies, tools and strategies is the advantage of collaborative work in the North America.²

1.1.3 Evolution of LCA in building sector

Since 1990s, LCA has been applied to assess environmental impacts of products and materials in the building construction. Various standards have been developed so far in order to facilitate environmental evaluation based on LCA (ISO 14040 and ISO 14044), and more specifically for Type III environmental declarations (ISO 14025: 2006 the LCA based mechanism, more commonly known as Environmental Product Declarations (EPD)).

Beyond existing guidelines, norms and regulations, two methodologies are applied widely to the building and construction sectors in different countries and regions: Life Cycle Assessment (LCA) and Life Cycle Management (LCM). They cover a large scope from the products, to the building and beyond (e.g. city, district etc.[14]). Assessment in this sector also integrates social and economic aspects, related to this sector.

Although LCA is applied widely in building and construction, harmonization seems essential to mainstream LCA within construction sector. Some issues like, background life cycle inventory data, environmental impact indicators (e.g. resource assessment, which is subject of this work) and life cycle inventory modelling [15] are considered as three most important and significant elements, subject to development within LCA in the coming years.

1.1.3.1 Research in building and construction LCA

Construction industry, is one of leading sectors in LCA-development. The growing importance of LCA as a scientific and practical tool to evaluate sustainability aspects is a appositve trend. Nevertheless still many research opportunities and areas to improve

² <http://www.sustainabilityconsortium.org/>

current practice exist. The extended number of scientific studies in different building and construction related areas in different countries emphasize the application of LCA in this sector. A non-exhaustive list of the LCA studies and applications are classified and provided in Table 1-1.

Table 1-1 A non-exhaustive list of scientific publications in building and construction, classified per topic.

ID	Topic	Examples	Authors and year of publication	References
1	LCA for Construction/ building products and materials	Concrete, Brick, Wood, Standards/labels and tools Etc.	(Gursel and Ostertag, 2016; Lasvaux et al., 2016, 2015; Maia de Souza et al., 2016; Mendoza et al., 2012; Rajagopalan et al., 2012; Vieira et al., 2016)	[16]–[22]
2	Building Life Cycle Assessment	Residential/commercial buildings, Standards/labels and tools New methods, Etc.	(Collinge et al., 2013; Federal et al., 2015; Kofoworola and Gheewala, 2008; Lasvaux et al., 2014; Paleari et al., 2016; Russell-Smith and Lepech, 2015)	[15], [23]–[27]
3	LCA of construction related activities	Road construction, Bridge construction, Tunnel construction, Etc.	(Chowdhury et al., 2010; Du et al., 2014; Huang et al., 2015; Li and Chen, 2017; Takano et al., 2015)	[28]–[32]
4	LCA applied in sediments	LCA for dredged sediment placement strategies, LCA of contaminated sediments, Etc.	(Bates et al., 2015; Blanck et al., 2016; Chowdhury et al., 2010; Sibley et al., 1997; Sparrevik et al., 2011)	[28], [33]–[36]
5	Social and economic LCA	Social LCA, Life Cycle Cost, Etc.	(Atmaca, 2016; Dong and Ng, 2015; Hosseini et al., 2014; Onat et al., 2014)	[37]–[40]
6	LCA for End of Life management / construction and demolition waste management		(Bovea and Powell, 2016; Butera et al., 2015; Mercante et al., 2011; Sandin et al., 2013)	[41]–[44]
7	Urban and district LCA		(Fröling and Svanström, 2005; Jeong et al., 2015; Jian et al., 2003)	[45]–[47]

1.2 Methodological framework of Life Cycle Assessment

Based on ISO 14040:2006, LCA framework is designed based on four phases, (Figure 1-1):

1. Goal and scope definition (divided into two separate phases in ILCD handbook and PEF method)
2. Inventory analysis
3. Impact assessment
4. Interpretation

There are interactions between LCA phases as shown in Figure 1-1.

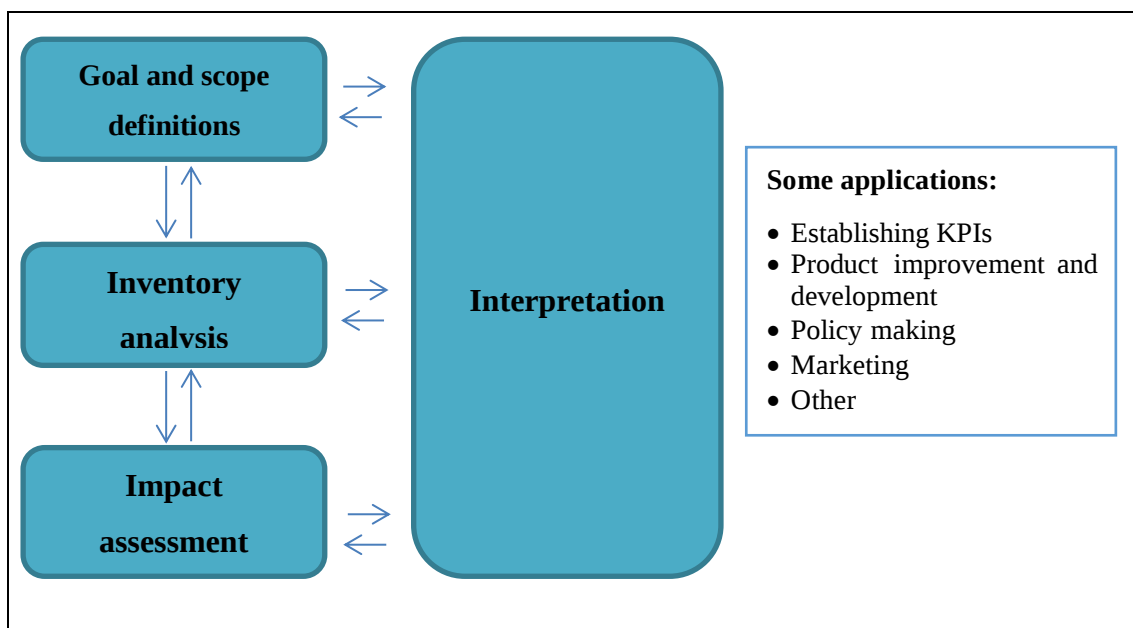


Figure 1-1 Framework of life cycle assessment (based on ISO 14040:2006).

1.2.1 Goal and scope definitions

1.2.1.1 Goals of the study

Goal definition is the first step of LCA, for both single-unit process and comparative LCA. This phase is the most decisive phase of the LCA and consists of defining the aims

of the study. The verification protocols, outlines and quality requirements of the work define the following facts. A clear, initial goal definition avoids misleading conclusions from initial LCA study. It can also limit the use of complete or part of the LCA beyond the initial goal and scope. Based on ILCD handbook [48] the following list is needed to be answered for goal of the study:

- Intended application(s) of the deliverables /results (IDEM ISO)
- Limitations due to the method, assumptions, and impact coverage
- Reasons for carrying out the study and decision-context (IDEM ISO)
- Target audience of the deliverables /results (IDEM ISO)
- Comparative studies to be disclosed to the public (IDEM ISO)
- Commissioner of the study
- Other influential actors

1.2.1.2 Scope of the study

In line with the goal of the study, details of objects of LCA study, includes life cycles stages and processes should be defined, too. So, the scope definition is to derive requirements on methodology, quality, reporting, and review in accordance with the goal of study. Bellow points on scope of the study should be defined based on ISO/ILCD handbook:

- The product system to be studied (ISO)
- The type(s) of the deliverable(s) of the LCI/LCA study, in line with the intended application(s)
- The system or process that is studied; its function(s), functional unit, and reference flow(s) (IDEM ISO)
- LCI modelling framework and handling multifunctional processes and products (called allocation in ISO)
- System boundaries (IDEM ISO), completeness requirements and related cut-off rules

- LCIA impact categories to be covered and selection of specific LCIA methods to be applied (IDEM ISO) as well as - if included - normalizing data and weight definition
- Interpretation to be used (ISO)
- Other LCI data and data quality requirements (IDEM ISO) regarding technological, geographical and time-related representativeness and appropriateness
- Types, quality and sources of required data and information, and especially required precision and maximum permitted uncertainties (ISO) have to be defined here
- Special requirements for making comparisons between systems identifying critical review needs (IDEM ISO)
- Planning the report of results (called format of required report in ISO)

Assumptions, values and optional elements and limitations are also required in ISO 14044.

1.2.1.3 Function, functional unit, and reference flow

1.2.1.3.1 Function, functional unit

In order to compare (specially the products) in a meaningful and correct way, it is important to define function of the system (provided service) and to verify the unit measuring the function, called Functional Unit (FU). Detailed description of the function(s) provided by applied analyzed system is called functional unit in the LCA. The functional unit should be consistent with the goal and the scope of study.

Some questions like “what”, “how much”, “how well”, and “for how long” should be answered in order to define and precise the functional unit.

To make it further clear, following examples split four aspects: for example an insulation product applied in a building wall. A thermal insulation product is a product

whose primary function is to reduce heat transfer³ through the building elements against which, or in which, it is installed.

- "What" a wall insulated with an **insulation product**⁴ that reduces heat transfer through the building element
- "How much": The amount of products needed to **insulate 1 m²** of building wall.
- "How well": A thickness that gives an **overall heat transfer coefficient**⁵ of X ($U_c = X \text{ W}/(\text{m}^2 \cdot \text{K})$).
- "How long" for a design life of 30 years.

The functional unit of the thermal insulation is defined then as:

"Thermal insulation of 1m² of a building wall, with an insulation thickness that gives an overall heat transfer coefficient of the wall equals to X ($U_c = X \text{ W}/(\text{m}^2 \cdot \text{K})$), with a design life span of 30 years".

1.2.1.3.2 Reference flow

Two similar definitions are used in the LCA to define a reference flow:

The first definition: Flow or flows that all inputs and outputs (Waste flow or elementary flows) are quantitatively associated with fulfilling the function, i.e. functional

³ Heat is transmitted in three different ways – convection, conduction and radiation. Heat flows naturally from a warmer to a cooler medium. In winter, the heat moves from all heated indoor spaces to the outdoors and during summer, heat might move from outdoors to the interior of the building (when the outdoor temperature is higher than the indoor temperature).

⁴ Thermal insulation is identified based on thermal resistance, known as the R-value, which indicates the resistance to heat flow (heat transfer per unit area per unit time). The higher the R-value, the better the insulating effectiveness. The R-value of thermal insulation depends on the material's thermal conductivity and its thickness and is equal to $R=d/\lambda$ (expressed in $\text{m}^2 \cdot \text{K}/\text{W}$). ("d" represents the thickness and λ the thermal conductivity.)

⁵ The U-factor or "U-value", the overall heat transfer coefficient, is a measure of heat loss through a material or building element such as a wall, floor or roof $U=1/R_T$ (expressed in $\text{W}/\text{m}^2 \cdot \text{K}$). A low U value indicates high heat resistance.

unit. It can also be directly expressed by functional unit. For example, in case of thermal insulation, the flow can be quantity of materials, in *kg*, used to cover a specific functional unit. The choice of reference flow depends first of all on type of products. For those products with several functions, a measured amount (e.g. mass in *kg*) with its technical specification might be more useful.

The location also is an important point to be defined in functional unit and reference flow, including transport and storage phase.

The second definition: Based on Jolliet et *al.* (2010), reference flow is a quantified amount of a required product(s), purchased products included, to provide a functional unit [49].

The aim of reference flows is to translate functional unit into specific quantitative product flows for comparing systems.

1.2.1.4 System boundary

The system boundary is defined to describe a supply chain (processes) and scenarios (upstream, downstream and transport), to give an insight into life-cycle stages, processes or necessary data. All decision to include or not to include any life cycle stages or processes should be described in detail in the system boundary.

1.2.1.5 Life Cycle Inventory modelling framework

There are several decisions to be taken during scope definition for the inventory modeling and framework. System details like attributional or consequential modelling and allocation or system expansion / substitution approaches are some issues to be defined during this phase. The goal of study is a crucial point to consider in defining Life Cycle Inventory modelling framework.

1.2.1.6 Critical review

For controlling quality and credibility of LCA results, a critical review is done by an expert. Different types of critical reviews (panel, individual, etc.) are performed based on goals and scope of the study. There are several available documents that define the minimum requirements, review scope and documentation for an LCA critical review. The critical review should be performed by experts, not involved in the LCA study.

1.2.2 Life Cycle Inventory

1.2.2.1 Introduction

Life Cycle Inventory (LCI) consist of developing an inventory of flows from and to the nature for a product system. Inventory flows include raw materials and energy inputs, and emissions to the air (space), water, and land. The input and output data, needed for construction of a model are collected for all the activities within a system boundary, including a complete supply chain (referred to as inputs from the technosphere) [12].

Data must be related to the functional unit and reference flow, which were defined in the goal and scope phases. The results of inventory is an LCI, which provides information about all inputs and outputs in the form of elementary flow⁶ to and from the environment from all the unit processes, involved in the study.

The modelling in LCA is based on two specific approaches: attributional and consequential modelling. The processing procedures within the system boundaries differ considerably between two types of modelling in LCI phase.

⁶ material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation (ISO 2006)

1.2.2.2 Data collection, acquisition, and modelling

Data collection and modelling of the system are done during the LCI analysis stage. Like all other phases, the goal and scope of the study should be carefully considered. The LCI phase provides results for all next LCA steps. In some cases, scope of the study can be readjusted during this stage.

Three main steps are done during LCI phase: data collection, acquisition, and modelling. The LCI is the main and the most important time and resource consuming phase in the LCA. For all additional non LCA indicators, separated inventory and interpretations might be provided in LCI phase.

1.2.2.2.1 Type of data

As mentioned previously, the inventory and data collection is one of the most time consuming stages in LCA. In order to reduce the costs one should be defined prior to data collection, the required data sources and the data types. It is suggested to collect specific industry data for production processes.

Two major data types are collected in the LCA: Generic data, which is representative of industry averages, and brand-specific level data. There are two data sources [50]:

- Primary data: collected mainly from interviews, questionnaires or surveys, Bookkeeping or enterprise resource planning (ERP) system, data collection tools (online or offline) and onsite measurements.
- Secondary data: collected in databases, statistics and through the literature review.

Data can also be classified based on the way they are developed: site specific, modelled, calculated or estimated, non-site specific (i.e. surrogate data), non LCI data (used for other purposes) and vendor data.

1.2.2.3 Attributional and consequential modelling

1.2.2.3.1 Attributional modelling

The attributional life cycle inventory modelling describes the potential environmental impacts that can be attributed to a system over its life cycle: from material extraction, to its use and end-of-life. Attributional modelling is conducted using historical, fact-based, measureable data of known (or at least know-able) uncertainty, and includes all the processes that are identified to relevantly contribute to the system under study [12].

1.2.2.3.2 Consequential modelling

Consequential modelling is a modelling approach to define consequences of a decision for other components of economy processes or systems both internally on the system and on other external systems. In consequential modelling, a hypothetical value chain (not reflecting the actual or forecasted, specific or average situation) is modeled, including specific market mechanisms and potentially including political interactions and consumer behavior changes [12].

1.2.2.4 LCI method approaches for solving multi-functionality

In most cases, more than one input is needed to perform a process, alike a process may deliver several products. In case that a process or a facility provides more than one function, i.e. it delivers several goods and/or services (co-products) the system is considered as “multifunctional”. In these situations, all inputs and emissions, linked to the process, must be partitioned between the product of interest and other co-products in a principled manner.

Regarding the multi-output processes the EN 15804 and PEF [13] draft method (Product Environmental Footprint) follow more or less the same decision hierarchy:

- Subdivision
- System expansion (case of PEF method)
- Allocation based on

1. a relevant physical relationship
2. other relevant relationship

Allocation should be avoided as far as possible by dividing the unit process or by system expansion.

1.2.2.4.1 Subdivision of multifunctional processes

The only exact method to solve the multi functionality issues correctly, is using subdivision. This approach consists of solving the problem by dividing system and extracting the mono-functional processes that is related to the analyzed system. It is often possible to avoid allocation by subdivision.

The problem of multi-functionality is solved by subdivision if the subdivided processes are not still multifunctional. Even if all multifunctional processes are not divided into mono-functional processes, the quality of data and results are improved in case of partial subdivision.

Subdivision can be applied by both attributional and consequential modelling.

1.2.2.4.2 System expansion (including substitution)

The system expansion⁷ is done following two main steps:

- expanding the system boundaries
- substituting the function with an alternative way of providing it

⁷ Example from ILCD handbook: Blast furnace slag is a joint co-product of steelmaking (typically in the range of 0.2 to 0.35 kg per kg hot metal). It is mainly used in cement making (superseding Portland cement) and in road building (superseding primary aggregates), while a smaller part is not used, i.e. deposited. If we want to obtain exclusively the life cycle inventory of producing blast furnace steel, the inventory of the co-function blast furnace slag will be eliminated from the process by subtracting the inventory of the superseded processes. In this way, we can obtain an LCI data set exclusively for the production of the steel from this process/plant. Here we have expanded the system's perspective by subtracting the not wanted function(s) via the life cycle inventory of alternative means to provide it.

The other use of system expansion is when several multifunctional systems are to be compared in a comparative study. As an example, a cellphone with several applications: phoning, internet surfing, taking photos, etc. This would be done by expanding the system boundaries and adding for the given case missing functions and the inventories of the respective mono-functional products: For example, in case of cellphone an inventory of camera will be added to the initial modeling.

1.2.2.4.3 Allocation

Allocation is the last step in solving multi-functionality issue. It solves the problem by fragmenting the sum of all inputs and outputs between co-functions according to a defined criterion. As examples, mass, energy content, market value, etc. are some of allocation criteria, used in LCA.

First of all, allocation should be done based on fundamental physical, chemical and biological relations between different products or functions (According to ISO 14044).

When it is not possible to find clear common physical fundamental relationships between co-functions, ISO 14044 recommends performing allocation according to another link. This may be an economic or energy content.

1.2.3 Life Cycle Impact Assessment (LCIA)

1.2.3.1 Introduction

After grouping the emissions and resources in the phase of Life Cycle Inventory (LCI), impact assessment is then performed following different steps called Life Cycle Impact Assessment (LCIA). LCIA methods aim to connect, emissions and extractions of life cycle inventories (LCI-results) on the basis of impact pathways to their potential environmental damages [51].

Different impact categories like climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics,

ionizing radiation, eco-toxicity, photochemical ozone formation, land use, and resource depletion are included in LCIA. The emissions and resources derived from LCI are assigned to each of these impact categories based on different available impact assessment methods (Figure 1-2).



Figure 1-2 Conversion of inventory in environmental impacts.

They are then transformed into indicators using factors calculated by impact assessment models, called characterization factors. Weights per unit emission or resource consumed in the context of each impact category are reflected by these factors. An example of conversion of emissions of greenhouse gases to warming potential is provided in Figure 1-3. As illustrated in the figure, The Mass of CO₂ and N₂O is multiplied respectively with the Global Warming Potential factor (F_{GWP}) of each gas.

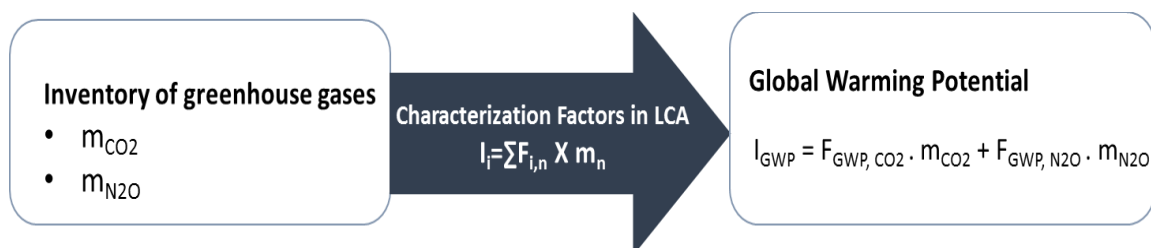


Figure 1-3 Example of conversion of emissions of greenhouse gases to global warming potential.

Two main aspects played a major role in development of Life Cycle Impact Assessment⁸:

⁸ It is important to note that the results of LCIA should be seen as environmentally relevant impact potential indicators, rather than predictions of actual environmental effects.

- Decision making in product development and need for better environmental information.
- New knowledge and models based on the development of environmental sciences.

Based on ISO, the LCIA stages consist of mandatory and optional steps which are listed below:

- Selection of the impact categories (to be considered in the goal and scope phase of a LCA),
- Assigning the inventory data to the chosen impact category(ies) (classification),
- Assessing impact category indicators using characterization factors (characterization),
- Normalization: calculation of category indicator results relative to reference values(s) (optional),
- Weighting the results (optional),
- Data quality analysis (highly suggested in comparative assertions).

1.2.3.1.1 Impact categories

LCIA methods can be grouped into two families [51]:

1- Classical methods (e.g. CML, EDIP and TRACI): They aim to determine impact category indicators at an intermediate position of the impact pathways (e.g. climate change, ozone depletion potentials, etc.); hence they are so called midpoint impact categories.

2- Damage-oriented methods (e.g. Ecoindicator 99: ReCiPe and EPS): They aim easier interpretable results in the form of damage indicators at the level of the ultimate societal concern (e.g. human health damage).

Midpoint indicators: A midpoint indicator can be defined as a level in a cause-effect chain or network (environmental mechanism) for a particular impact category where a

common mechanism for a variety of substances within that specific impact category exists.

For example, Global Warming impacts involve a series of steps, starting with the release of greenhouse gases, and ending with impacts on humans and ecosystems. There is a point where greenhouse gases have an effect on radiative forcing. Greenhouse gas emissions have a pathway that is different before that point, but identical after it. Therefore, the radiative forcing provides a suitable indicator for the midpoint impact category of Global Warming [52].

Some of the LCA midpoint indicators are listed below: Climate change, (stratospheric) ozone depletion, Human toxicity, Respiratory inorganics, Ionizing radiation, (Ground-level) Photochemical ozone formation, Acidification (land and water), Eutrophication (land and water), Eco-toxicity, Land use, Resource depletion (minerals, fossil and renewable energy resources and water).

Endpoint indicators: Endpoint indicators are calculated to reflect differences between stressors at an endpoint in a cause-effect chain and may be of direct relevance to society's understanding (areas of protection) of the final effect. Availability of reliable data and robust models to support endpoint modeling remains too limited based on a part LCA experts.

Below, a list of the suggested Areas of Protections (AoPs) in LCA: Human health, Natural environment, Natural resources [53].

Another approach is the LIME [54], developed by LCA national project in Japan. LIME develops a damage-oriented approach. The damage assessment categories are catalogued into four areas of protection: human health, social welfare, biodiversity, and plant production. Two types of weighting methods are used:

- 1- Amount of monetary value for avoiding a unit amount of damage to a safeguard.
- 2- Weighting coefficient based on an annual amount of damage to a safeguard subject.

LCIA methods exist for midpoint and for endpoint level, and for both in integrated LCIA methodologies. Both levels have advantages and disadvantages. In general, on midpoint level higher number of impact categories is differentiated (typically around 10), and the results are more accurate and precise, compared to the three areas of protection at endpoint level that are commonly used for endpoint assessments.

1.2.3.2 Characterization of impacts and damages

In order to calculate LCIA results, elementary flows are linked to one or several impact categories to accomplish the impact assessment on the midpoint and endpoint level. We call this stage a “classification” Figure 1-4 give a simple example of the mapping inventory data to impact indicators.

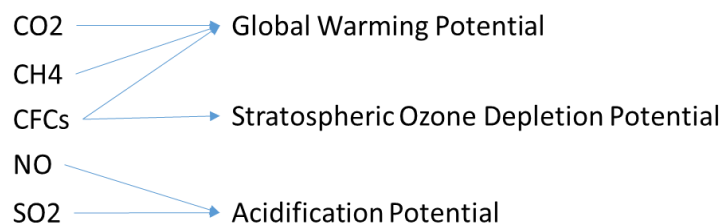


Figure 1-4 Example of the mapping inventory data to impact indicators.

Then the inventory results for each elementary flows are usually multiplied with relevant impact factors (characterization factors) from the corresponding LCIA method; this step is called characterization in LCA. Impact characterization uses science-based conversion factors, called characterization factors (also referred to as equivalency factors), to convert and combine the LCI results into representative indicators of impacts to human and ecological health. Characterization provides a way to directly compare the LCI results within each impact category. In other words, characterization factors translate different inventory inputs into directly comparable impact indicators.

Best available characterization models are identified in the study done by JRC published in ILCD handbook series [55].

Because of complexity of these steps, they are not done directly by practitioners. This part is done in research projects as a part of developing LCIA methods. However, one should check that all inventory elementary flows are correctly connected to the LCIA factors. In most of the cases a practitioner uses an LCA software to assure and simplify the correct connection between these components.

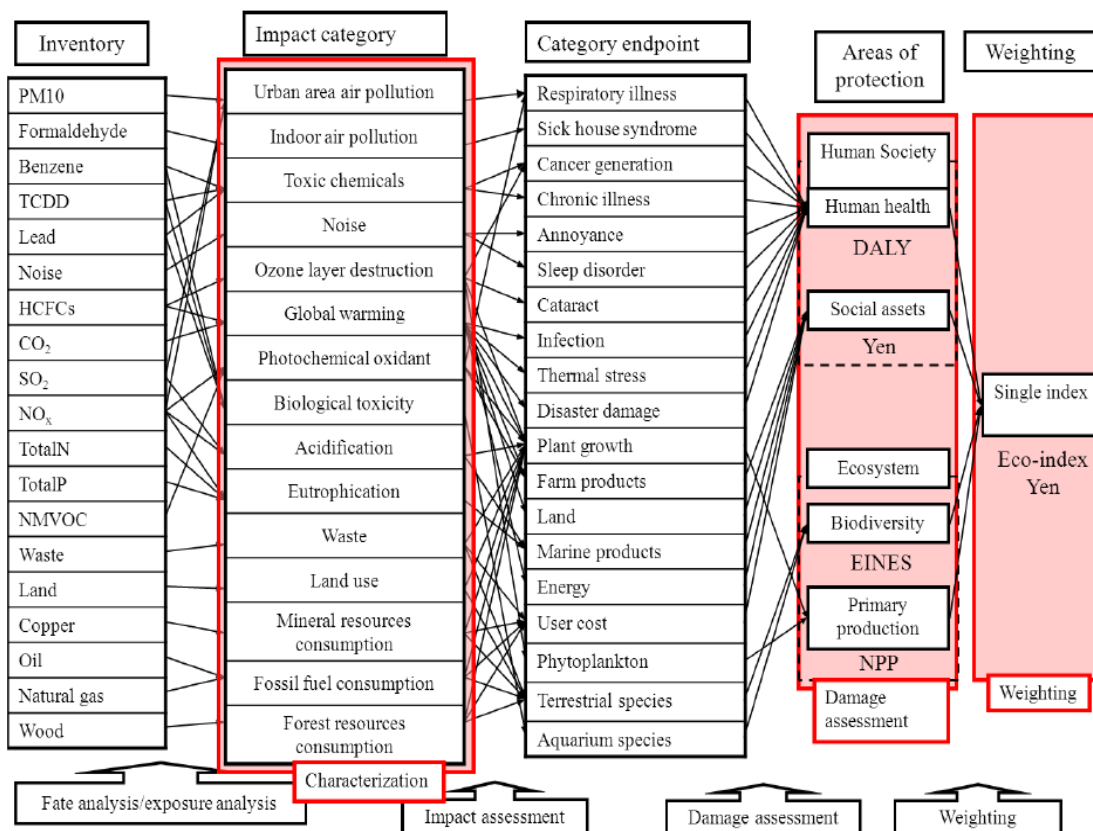


Figure 1-5 Characterization modelling at midpoint and endpoint levels from LIME2 method [56].

As different impact categories have different units, results cannot directly be compared and cannot be summed together. Classified and characterized elementary flows that are “linked” with the LCIA methods are normally available in LCA software.

1.2.3.3 Optional Elements: Normalization and Weighting

Two optional steps of LCIA under ISO 14044 are Normalization and Weighting. Normalization as the first step supports the interpretation of the impact profile and is the first step to aggregate result. In the next step, weighting transfer separate quantitative weights to all impact categories to express their relative importance.

Normalization is done to help the use of LCIA indicator results into a broader context and adjust results to common dimensions. To do so, the sum of each category indicator result is divided by a reference value.

For each impact on midpoint or endpoint level, normalized LCIA results give a relative share of the impact using overall indicator results, e.g. per average citizen or per country, etc. In this way when different normalized impact categories (midpoint and endpoint) are presented, one beside the other, so one can see the relative importance of each of them.

Like Normalization, different weighting methods are classified in different ways in LCA presented in detail in different publications [57].

1.2.3.4 LCIA methods

The collection of individual characterization models addressing separate impact categories is called LCIA method in LCA. Different LCIA methods are developed in the framework of LCA. These methods provide a framework to progress from inventory flow to the characterization factors. Some of them also provide a way to progress from midpoint to endpoint indicators by different concepts. The Figure 1-6 reveals a timeline on the development different LCIA methods.

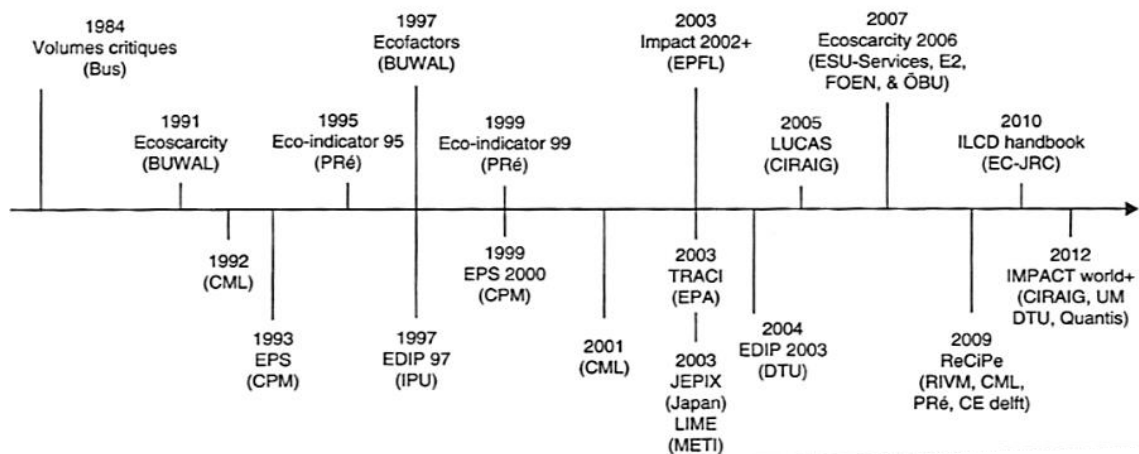


Figure 1-6 Timeline of the most common LCIA methods in LCA [58].

1.2.4 Interpretation of results

In LCA, the phases are as important as the final result. The importance of interpretation is also because it evaluates results of all the LCA steps. The interpretation must also highlight the methods used and shall clearly state the limitations of the study. The interpretation is considered as the last phase of an LCA study; and helps answering the original question, defined in the goal of the study.

The interpretation seeks reliable conclusions from LCA study and seeks to define and study environmental hotspots of a product or a service. For this purpose, it is necessary to analyze the results, define the limits of the performed study. Interpretation can help improving the Life Cycle Inventory model to meet the needs derived from the study goal.

Verification of the study is included to improve the confidence and reliability of results. For this step, three essential points should be evaluated: completeness and sensitivity analysis, as well as potentially uncertainty analysis for the determination of precision of results.

The sensitivity control contains the evaluation of the reliability of the final results. The completeness checks to ensure that relevant information and data, required for the interpretation, are provided completely.

If information is missing or incomplete, they need to be analyzed. There are two possibilities: either life cycle inventory must be reviewed or definition of goal and scope of the study must be adjusted.

1.3 Context and aim of this work

Sustainable buildings and construction are the fabric of sustainable lifestyles. Whilst public and industry understand the importance of energy efficiency, the environmental impacts of the building and construction related activities, products, materials and their associated end of life are remained less known. For an energy-efficient house, the embodied energy in the construction represents more than 75 years of heating in equivalent energy [59]. To assess environmental impacts of a building and construction, it is necessary to consider the overall lifecycle (from design to the end-of-life) [60]. LCA appears to be an ideal approach to get this clear global view and helps in making decisions based on scientific facts [61]. All aspects considering natural environment, human health and resource depletion are taken into account. LCA avoids problem-shifting between different life cycle stages, between regions and between environmental problems.

From resource prospective, building and construction sector is responsible for more than third of global resource consumption, including 12% of the fresh water use and its generation of solid waste is estimated to be 40% of the total waste volume [62]. At European level, construction and demolition waste is the largest waste stream representing one third of all waste produced in EU [63]. Therefor the resource efficiency and management is crucial in building construction and beyond. The aim of this work is to propose reliable and applicable indicators in the framework of LCA and Circular Economy to assess the resource impacts and benefits (extraction and recycling).

2. Resource indicator in Life Cycle Assessment

Highlights:

- Upstream and downstream key resource related concepts are defined.
- Existing resource assessment approaches and developments in LCA are introduced.
- Missing or contradictory aspects, related to LCA resource impact assessment methods are argued.
- A common framework for assessment of resources is proposed.

2.1 Introduction

Since development of LCA in the early 1990s, the impacts from resource use have been a part of LCA. However, even if a variety of life cycle impact assessment (LCIA) methods already assess resources depletion as an impact category, impact assessment of resources in general and metallic mineral in particular is one of the most controversial issue in LCIA.

First of all, the methods lack both in the number and types of covered resources. As an example, missing rare earth elements characterization factors [64], [65]. In addition, lacking consistency has hampered the development of widely acceptable indicators for the resource use [66]. This was also highlighted by the recent International Reference Life Cycle Data System (ILCD) handbook of the European Commission (EC) Joint Research Center (JRC) [67]. It suggests the need for methodological improvements. This lack of consensus on how resource depletion should be addressed urges - according to the EC - for the development of a harmonized LCIA method for the resource use [68].

The missing alignment among different LCIA methods for resource use impact comes not only from differences in the modeling nature, but also from the differences in definitions and understandings of what the resource problem is, what limits the access to resources and why there is a need to consider resources as an Area of Protection (AoP) as such. There is an obvious paradox compared to the existing resource assessment methods, as in theory all agree that what has to be protected is the access to a functional value of the resources. That means the services, provided by resources are what the society has to protect, not the resource for the sole value of its existence. However, in practice most LCIA methods are only based on geological and recently anthropogenic availability of resources without any consideration of their functionality or of the multiple barriers for their access.

LCA indicators are developed for evaluating criticality, economic and social aspects of the resources. The indicators, could be estimated at two levels: midpoint and endpoint.

At midpoint level, the extraction of a particular resource (biotic or abiotic) is concerned, and indicators are usually based on mass. At endpoint level viewpoint, consequences of extraction, e.g. in environment, becomes important.

2.2 Classification of natural resources in LCA

Resource is a broad term that may encompass elements, including static material (e.g. minerals) and fluctuating phenomena (e.g. wind). Resources can be classified from different viewpoints: components (biotic or abiotic), origin (natural or anthropogenic), function (energy, mineral [metallic, non-metallic]), water, soil, plant or animal or renewability (renewable, non-renewable). Functional perspective of resources can be defined more precisely, using their intrinsic properties. For example, mineral resources are often characterized by concentration degree (or grade), while energy resources are often distinguished by their calorific value. Within the context of LCA, natural resources are generally categorized into: abiotic and biotic resources; renewable and non-renewable resources or stock; fund and flow resources. The following categorization and definitions are proposed by UNEP SETAC Life Cycle Initiative [69].

Abiotic resources are inorganic or non-living materials at the moment of extraction (e.g. water, metals, also dead organic matter such as peat or coal; cf. UNEP 2010).

Biotic resources are living materials at least until the moment of extraction from the nature (e.g. wood or fish). In addition, industrial biotic resources (e.g. fish from aquaculture, wood from plantation, agricultural crops, etc.).

Renewable resources are those resources that renewal rates are not much less than the human rate of consumption.

Stock resources exist as finite, fixed amounts in the environment, with no possibility of regrowth (e.g. rocks, metals). In other language, renewal rates are much larger compared to the human rate of consumption (e.g. oil).

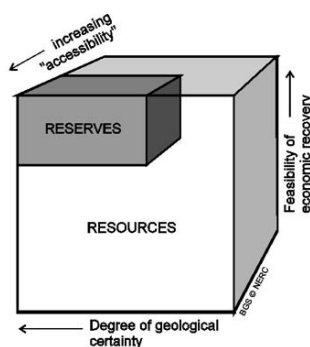
Fund resources should be depleted at a rate, keeping the ratio of extraction inferior to regrowth (renewal rate). Either permanent depletion (i.e. the extinction of a species) or expansion of a fund (if renewal rate exceeds extraction rate) are possible.

Flow resources are resource types that do not deplete although there might be local or temporal non-availability (e.g. surface freshwater, which is dependent on precipitation, solar or wind energy). Evidently, renewability of flow resources is instantaneous.

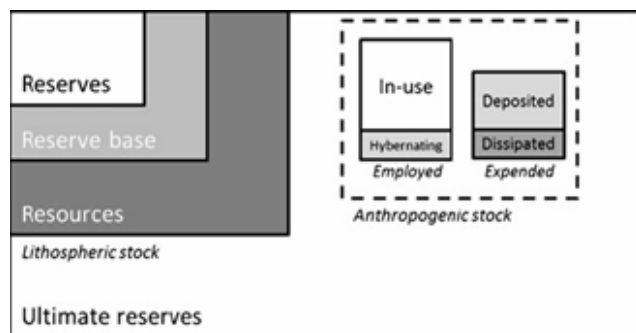
2.3 Resource or reserve?

Sometimes, these two terms are confused. Addressing earth resources, “resource” is a more general term, compared to “reserve”. Resources are available in various forms within the lithosphere. These potentially available materials are neither necessarily accessible nor extractable economically or technically.

The concept of reserve is assigned to some part of available resources that have the property of feasibility of extraction (technical aspect) and is profitable to invest on the extraction (economic viability). A didactic representation of these concepts was introduced [NERC BGS], and is illustrated in the Figure 2-1a. Another representation is provided by USGS, Figure 2-1b.



(a)



(b)

Figure 2-1 Didactic representation of reserve versus resource (a) introduced by [NERC BGS] (b) by USGS

Definitions by USGS are provided below:

- **ultimate reserves:** amount of materials, ultimately available in the earth's crust. The definition includes unconventional and low-grade materials and common rocks.
- **resources:** concentration of minerals in ore inside the earth's crust with high risk of extraction.
- **reserve base:** some parts of resources that have minimum physical and chemical criteria at the moment but are not necessarily extractable, economically.
- **reserve:** the rich deposit that is feasible to be mined, economically and technically.

2.4 Recyclability

As an extreme case, metals recyclability may reach to 100%, i.e. ideal recovery without any loss of quality in the far future. Metals can be reused many times without losing their functionality, but cannot be regenerated in the ore deposits. The ideal recyclability might not be reached due to losses during extraction, use, transformation, transportation, etc.

Here, we discuss the recycling rates, developed by the United Nations Environment Programme's (UNEP's), International Panel for Sustainable Resource Management [70]–[73]. The report provides several parameters on 60 metals, classified into 4 groups: "ferrous, nonferrous, precious and special metals". Most of these metals are used in building and construction sector. The list of parameters, used to obtain recycling related factors is provided in Figure 2-2.

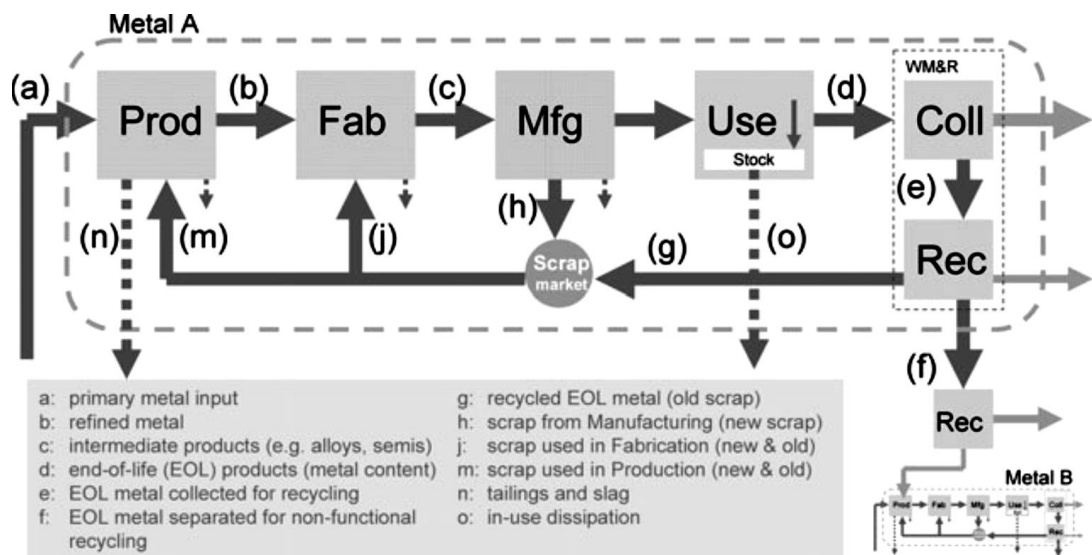


Figure 2-2 Flowchart of life cycle of a metal [73].

Prod = production; Fab = fabrication; Mfg = manufacturing; WM&R = waste management and recycling; Coll = collection; Rec = recycling. Yield losses at all life stages are indicated through dot-lines (in waste management [WM] referring to landfills.)

Below indicators are estimated and agreed based on formulas, and are available in UNEP report: [74]

$$\text{End-of-Life functional recycling rates (EOL-RR)} = \frac{\text{recycled EOL metal (old scrap)}}{\text{EOL product (metal content)}}$$

Relation 2-1

This factor is related to the form of which the substance specific recycling occurs. It describes the amount of metal that is collected but lost for functional recycling, then becomes an impurity or "tramp element" in the dominant metal in which it is collected (e.g. copper in steel)

$$\text{Recycled content (RC)} = \frac{\text{scrap used in fabrication and production (old and new)}}{\text{primary metal input + scrap used in fabrication and production (old and new)}}$$

Relation 2-2

It provides a clear idea on how much of the EOL metal contained in various discarded products is collected and is entered to the recycling chain.

Old scrap ratio (OSR) =

$$\frac{\text{recycled EOL metal (old scrap)}}{\text{scrap from manufacturing (new scrap) + recycled EOL metal (old scrap)}}$$

Relation 2-3

This factor helps to understand the degree of the use of scrap from various stages of the metal life cycle which is occurring.

- New scrap is also called prompt scrap because of its known properties, high value and purity: its recycling is economically beneficial and easy to accomplish. New scrap is included in recycling statics.
- Old scrap is a metal in products that have reached their EOL. The recycling requires more effort, especially when the metal is a part of a complex product.
- Nonfunctional recycling is a portion of EOL recycling that the metal is collected as old metal scrap and incorporated in an associated large-magnitude material stream as “tramp” or an impurity element.

The results of End-of-Life functional recycling rates (EoL-RR), obtained and provided in the Supporting Information of the report on the Web are listed in Table 2-1.

Table 2-1 Recycling rates of some metals given by the appendices in the Supporting Information on the Web from [2], [71]–[73].

>50%	>25-50%	>10-25%	>1-10%	<1%
Al, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Nb, Rh, Pd, Ag, Sn, Re, Pt, Au, Pb	Mg, Mo, Ir	Ru, W, Cd	Sb, Hg	Li, Be, B, Sc, V, Ga, Ge, As, Se, Sr, Y, Zr, In, Te, Ba, Hf, Ta, Os, Tl, Bi, All lanthanides except Pm
Nb, Ru, Pb	Mg, Al, Mn, Fe, Co, Ni, Ge, Mo, Rh, Pd, Ag, In, W, Pt, Au, Hg	Be, Ti, Cr, Cu, Zn, Ga, Cd, Sn, Sb, Ta, Re, Ir	Se, Zr, La, Ce, Pr, Nd, Gd, Dy	Li, As, Y, Ba, Os, Tl, Sm, Eu, Tb, Ho, Er, Tm, Yb, Lu
Cr, Fe, Ni, Rh, Pd, Ag, Cd, W, Ir, Pt, Au, Hg, Pb	Mg, Al, Mn, Co, Cu, Zn, Nb, Mo, Sn, Re	Be, Ti	Ru, Sb, Ta	Li, Ga, Ge, As, Y, In, Ba, Os, Tl, Bi

2.5 Resource assessment in Life Cycle Assessment versus Circular Economy

The resources are extracted from the ecosphere in form of materials which are used in goods and products. The products, once their functional life ends, are either reused, recovered into recyclable materials, transformed, landfilled or dispersed in the nature. The resources in different states may be grouped generally into three environments: naturals, material and products (cf. Figure 2-3).

Products and materials are two phases of a larger environment: anthropogenic. LCA focuses on the damages, caused by human, also the exchanges between the nature and material phase. In another way, LCA assesses the exchanges from ecosphere to technosphere and vice versa. Meanwhile, Circular Economy focuses on the exchanges between material and product phases. It aims to close a loop to obtain the maximum share of necessary materials from the recycled part.

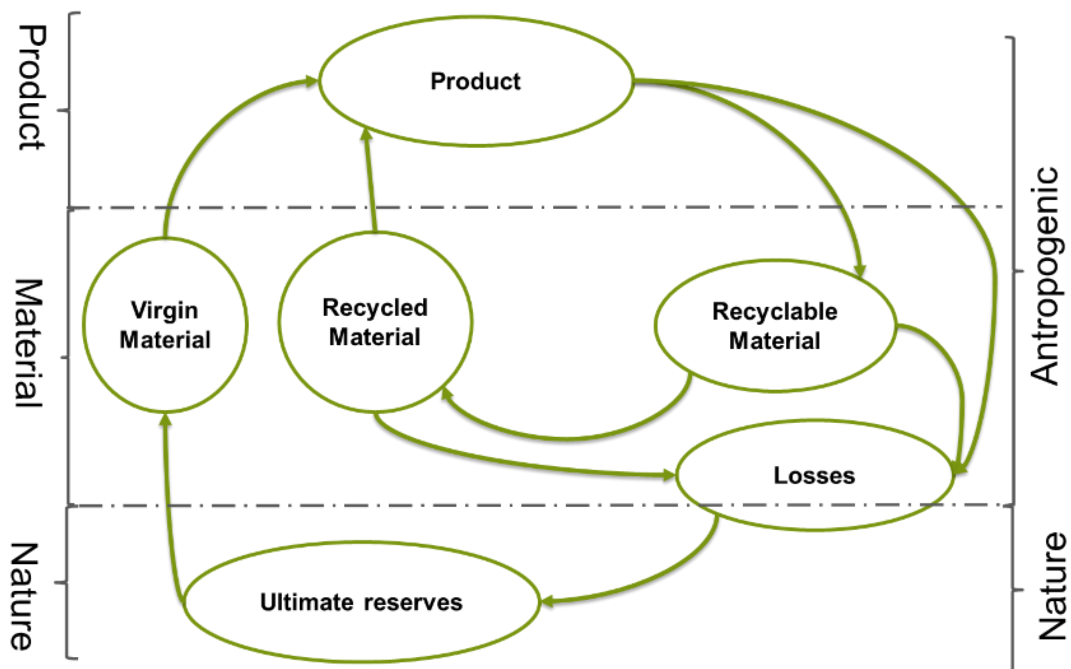


Figure 2-3 The circular nature of the materials between three environments: nature, material and product.

Four environments, six stocks and seven rates are basic concepts, used, which are defined successively within the context of this work, illustrated in Figure 2-4.

- Nature (ecosphere): part of the universe, not manipulated by the mankind. The nature is considered as the original environment of materials.
- Anthropogenic environment: refer to any changes in the nature that are caused by people. In another words, part of the universe, manipulated by the mankind.
- Material environment: part of anthropogenic environment, which is available in form of substance.
- Product environment: part of anthropogenic environment, including: manufacturing, product use and end of life waste, where materials stay during their lifetime.
- Reserve stock: an explored or exploited stock within the nature. There are several categorizations for the reserve due to being economic, technically extractable, etc. In the extreme case, reserve stock covers all the available resources in the earth's crust called ultimate reserve.
- Virgin material stock: It is a transition between reserve stock and the final product. The materials in this stock are under extraction and processing for adding values.
- Extraction rate: It is the rate of extraction of the materials from the virgin material stock extracted initially from reserve stock. It could be expressed in unit of mass per unit of time, e.g. ton/year.
- Product stock: They are materials, in form of products in this stock, reaching their highest economic value, and they stay within this stock for a lifetime.
- Recyclable stock (recovery): They are recoverable materials from the product stock. The function of this stock is similar to reserve stock.

- Recovery rate: rate of recovering scraped or used materials, after finishing their lifetime.
- Recycling rate: part of recovered materials which are recycled into the recycling stock.
- Dispersion: loss due to the unrecovered part of the production stock.
- Degradation: loss due to degradation of the materials during recycling.
- Recycling stock: part of recovered material that is being recycled.
- Recycled content: part of recycled material that is used as secondary material in the products.
- Transfer to ecosphere: losses are in fact transferred back to the ecosphere. It is here considered as a part of nature because at the moment it is not under the control of the mankind.

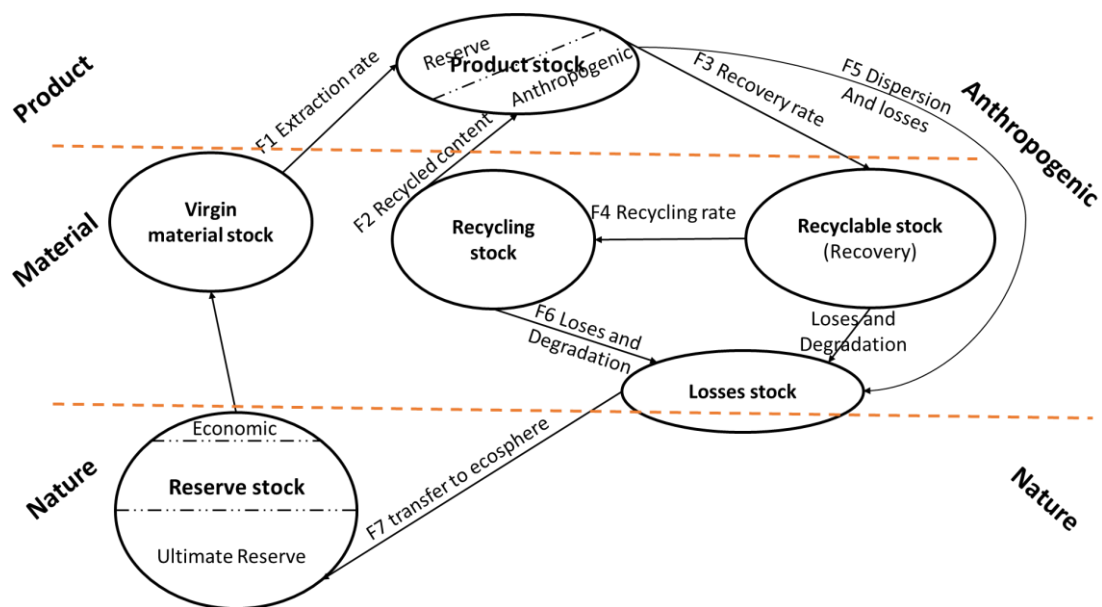


Figure 2-4 Material flow between the stocks.

2.6 Introduction to resource Life Cycle Impact Assessment methods

2.6.1 Exergy Method

This method could be used for assessing large variety of resources: biotic and abiotic: minerals, metals, fossil and nuclear fuels, wind, solar and hydropower, land occupation, atmospheric and water resources. Its indicator, X factor, reveals the exergy content per unit of the resource flow. Exergy is defined as “the upper limit of the portion of a resource that can be converted into work” [75]. But, exergy extraction means “extracted potential for entropy production from the natural environment” [76]. Reminding that the extracted portion of the resource is usually concentrated in within the industrial processes. So, the exergy loss is defined as the amount of energy, necessary to bring back the extracted portion of the resource into the non-concentrated state, before extraction [76].

2.6.2 Depletion-based Methods

These indicators are only developed for the abiotic resources, since the total amount is assumed known and non-renewable. They are based on two specifications of the abiotic resources: reserve and/or extraction rate. The main methodologies under this category are: CML, EDIP, AADP and Vieira *et al.* (2012).

One of the most famous indicator is Abiotic Depletion Potential (ADP), developed by the Institute of Environmental Sciences and included in the CML method [77], [78]. ADP is a dimensionless indicator. It is calculated by dividing the annual extraction rate of the resource, by the square reserve. Then, normalizing by the same ratio of the element antimony. The normalizing is only for making the ADP dimensionless, to be able in comparing it in different resources. The power two of the reserve in the formula, strengthen the effect of the reserve value, comparing to the extraction rate.

In the method of Environmental Design of Industrial Products (EDIP), the annual extraction rates are discarded; i.e. the current importance of the resource is not considered.

The EDIP indicator is the ratio of the total extracted value to the economically exploitable reserve [79].

The extracted part of the resources is neither considered in CML nor EDIP methodologies. Part of extracted amount will remain in the anthropogenic stock for hundreds or thousands of years. Archeologic and cultural layers are the extreme examples. So, the extracted minerals will be used or reused by the human. Schneider *et al.* (2011) [80] rendered this portion as “anthropogenic stocks”, and developed a new indicator: Anthropogenic stock extended Abiotic Depletion Potential (AADP). It is proved that incorporating anthropogenic stocks significantly changes the raw material availability. Recyclability of the metals is a controlling factor in defining anthropogenic stocks.

In the final method, dynamicity of cut-off grades is incorporated in calculations. Decrease of minable cut-off is a technological shift. Also, price increase results in decrease of economic cut-off. So, during decades, the cut-off values vary, consequently the reserves are dynamic in a large time-scale [81].

2.6.3 Surplus Energy Method

Taking into account the fact that the quality of the extracted portion does not remain constant during the extraction life-time, surplus energy method is developed. The extraction takes place from higher grades and easily accessible resources, primarily. Therefore, the resource quality decreases as a function of the time. Furthermore, more energy is required for extracting the remained lower-grade portion of the resource [82][54]. Its indicator for present resource depletion is defined as the required future energy for extracting from lower-grade deposits [83].

2.6.4 Marginal Cost (ReCiPe) Method

A universally applicable indicator is provided, monetizing the required energy for extracting the resource [84]. Marginal increase of extraction cost per kilogram of

extracted resource is the fundamental for the ReCiPe 2008 method. The extracted amounts are converted to the reference substance, which is iron. In fact, the method follows a similar idea as the surplus energy one, while monetizes the surplus energy demand for future extraction.

2.6.5 Willingness to Pay (WTP) Methods

In WTP, the substituting cost of a substance by a sustainable alternative is a value for future generations. For the cost of substitution, the market prices are used as basis. The goal in WTP models is to keep the monetary cost of avoiding damages to availability of resources. EPS 2000 is one of the WTP methods that uses resource depletions in weighting the impacts. For the case of metals, they are considered as non-substitutable but there is no sustainable alternative. So, the reference is set to be one kilogram of the resource, mined in the present; i.e. present reserve.

2.6.6 Distance to Target

There are some limitations in the material supply: environmental, policy-based, market demand, carrying capacity, etc. These limitations, provide critical flows, e.g. constraints for the production rate. The ratio of critical to actual flows is a base for distance to target approach. The method is well-developed for some resources only in the Switzerland [85].

2.6.7 Resource assessment methods in LCA

The environmental impacts, associated with the use of resources, minerals, metals, etc., are addressed in LCA, using different approaches [52], [68], [86]–[90], categorized initially by Stewart and Weidema [91] followed by Klinglmair et al. [88]. More recent works evaluates the current LCIA methods with regard to mineral resource depletion potential [90]. The four following groups of methods could be identified in the context of LCA resource assessment that are discussed previously in this chapter:

Group 1: Methods such as entropy production or exergy consumption [75] which are dealing with inherent characteristics of resources.

Group 2: Methods which address the scarcity of resources: the ratio of extraction to a measure of available resources or reserves, is the core of the methods of this group, e.g. EDIP [92] and CML [77], [78]. Few methods of this group cover the renewable rates for biotic resources. More recent works include the anthropogenic stocks for metals [80], [93], [94].

Group 3: Although LCA focuses mostly on the geophysical availability of the resources, the criticality of resources is also introduced and discussed recently within the framework of LCA [66], [93], [95]. Availability of resources as a more wider term is proposed within LCA framework [90] also the so called ESSENZ method [96] where socio-economic availability is introduced as a new dimension in resource assessment beyond physical availability of resources.

Group 4: Methods based on environmental impacts of the future extractions: these methods are based on additional energy and cost of extraction for future extractions. The scarcity of metals extracted include surplus ore produced, surplus energy required, and surplus costs in the mining and the milling stage. Methods are available today within the LCA framework, e.g. EcoIndicator 99 [82], ReCiPe [84] and Surplus Cost Potential [97].

Different approaches under the Life Cycle Assessment (LCA) framework are provided and used so far to address the resource consumption and production. However, they provide partial vision, based on limited available data, and do not reflect all the aspects related to different resources. Methods confuse in some cases resource depletion with impacts on resource availability [98]. Therefore, it is crucial to go beyond the current Life Cycle Impact Assessment (LCIA) methodologies in order to incorporate other important factors (e.g. recycling), not yet covered by the LCA resource assessment methods and to assess resource availability as a more meaningful and comprehensive concept [98].

2.6.8 Critical review of resource assessment in LCA

Group 1 methods focus on inherent properties of the materials. They cover relatively robust and certain characterization factors. Nevertheless, the resource problem is not

limited to the inherent properties of materials. Impact pathway does not describe the availability of a resource, and therefore the environmental relevance of these indicators is low. The scarcity of the resources is not part of these indicators.

In the group 2, the resource problem is only linked to the depletion from the earth crust [77], [78], [92]. Their environmental relevance is higher than the methods of the group 1. These methods reflect the problem of scarcity of the resources as production is going on. But, exploratory activities and development of extraction technologies have increased reserve availability during the past years [99]. Elements, extracted from the ecosphere are not vanished after their use [66], [90], [98]. They are transformed, alloyed, dispersed or coming back to the ecosphere directly, e.g. metallic compartment landfilled, or after a series of changes, e.g. energy resources.

Beyond the extraction from the Earth' crust, the methods of group two do not include recycling in the current LCIA models, leading to underestimation of total available substances within techno-sphere [86]. It is considered here that recycling and anthropogenic stock [80], [93], [94], is a promising initiation for evolution of the LCIA methods. The ratio of recycling rate to the anthropogenic stock plays the same role as the ratio of extraction rate to the extractable deposits. Within the context of the LCA, further development in modelling is necessary to incorporate recycling in both levels of inventory and impact assessment. In LCA, it is needed to go beyond geological or anthropogenic availability of the resources, also to include the difficulty of obtaining the resources which are available within either the techno-sphere or eco-sphere. The increasing attention on the expansion of circular economy proves the importance of recycling and accessible resources, besides depletion.

With regard to group 3, the criticality was assessed in European context by the Ad-hoc working group on defining critical raw materials [100]. Although LCA has focused mostly on geophysical availability of the resources, recently the criticality of resources is introduced and discussed within the framework of LCA [66], [93], [95], [96]. The concept was applied to several industrial minerals and metals in LCA [95], [96]. These methods

provide a new supply risk vision to the LCA. Nevertheless the fact that they are highly correlated with socio-economic aspects makes the prevision in future uncertain and generate high fluctuation in the results due to different interpretations. In addition the socio-economic parameters are numerous and complex to establish and update. Further work is needed to establish an applicable LCA method based on availability of resource and the current work is also an attempt in this direction.

The methods of the group 4 analyze the resource problem from the viewpoint of prediction of future extraction efforts. The main difficulty is the uncertainty of the future prediction. Also the complexity of parameters and methods restrain those to a very limited number of CFs. These methods cover only the resources available in the ecosphere as part of their scope of application.

The conceptual problems in the existing methods limits the coverage of the resource type significantly. Vast coverage of an LCIA indicator is a requirement for a comprehensive resource assessment. None of reliable LCIA methodologies provide full coverage over various resource types. Few methods cover the renewable rates for biotic resources. Some others, do not cover the energy resources. No distinction is made between fossil resources, being burnt in energy consumption or used for the non-energy purposes, e.g. plastics. In most cases, even when CFs are available, they are not comparable with different resource types, e.g. renewables versus non-renewable resources.

2.7 Resource Criticality and LCA

There is no precise definition for resource criticality, since its exact definition is subjective and principally depends on a specific context. [101] The National Resource Council (NRC) considers mineral to be critical "... only if it performs an essential function for which few or no satisfactory substitutes exist..." and "...only if an assessment also indicates a high probability that its supply may become restricted, leading either to physical unavailability or to significantly higher prices for that mineral in key

applications...".[101] Whereas, European Union (EU) defines critical raw materials as "...those which display a particularly high risk of supply shortage in the next 10 years and which are particularly important for the value chain...". [102]

The role of LCA for criticality assessment of resources is discussed recently by Sonnemann et al. [66] Criticality of minerals is highly relevant specially for metals such as REEs. The work from Graedel et al. provides a methodological approach to assess criticality of metals [103], which is also applied for the case of copper, Zinc, Tin and lead family [104], [105].

The method assesses the criticality of metal from three broad dimensions: supply risk, vulnerability to supply restriction and environmental implication. The supply risk dimension is not only focused on the availability of the resources but also includes other factors that may directly or indirectly affect the geological availability of resources. This includes social and regulatory, geopolitical, technological and economic indicators. The social and regulatory factors reflect the potential risk in which the society or the policy could impose on the resource extraction. The technological and economic factors refer to how the extraction is possible using the existing technology and whether it is economically feasible, respectively. The geopolitical factors deals with the potential risk associated with any political instability or political action.

Specific to the case of REEs in which their production and supply are dominated by a few countries with partial stability. The other dimension of metal criticality is vulnerability to supply restriction which refers to the importance of a given metal to a company or nation. It measures how the functionality of a company or a nation could potentially be affected by the supply disruption of a metal of interest. Here the substitutability of the metal is the most important factor among others. The third dimension addresses the environmental impacts associated with the life cycle of the metal.

Extraction and entire process of metal production are well known for their high energy intensiveness and also the high environmental impacts associated with [106]. Beside their

high energy demand on the extraction and production they also contribute to human toxicity. Therefore, it is important to include their environmental implication while assessing criticality. Generally the method proposed by Graedel et al. [103] could be seen as a mile stone for the development of criticality assessment. It could be used to further develop an operational LCIA method for resource which looks not only at the geological availability but also at other criteria. This issue is not yet addressed in the current LCA frameworks.

2.8 Framework to assess the resource depletion Characterization Factors

Existing LCIA methods for resource assessment are assessed here from different viewpoints. The assessment is conducted at different levels: (i) a conceptual framework, (ii) the basic assumptions, (iii) input parameters and (iv) availability and reliability of CF.

2.8.1 A conceptual framework

A conceptual framework is considered as the first criterion of resource assessment methods and reflects the comprehensiveness of methods to answer the resource problem. The indicator compares the goal of resource assessment, defined in different methods with resource related challenges, society is facing.

With regard to a conceptual framework, existing LCA methods are either based on inherent properties and depletion of materials, or based on prediction of future extraction efforts [91].

In addition, the methods do not provide a conceptual framework to assess all types of resources. This issue is usually associated with some considerations, behind the LCIA methods and some efforts are needed to develop new CFs.

2.8.2 The basic Assumptions

Different assumptions, theory and background exist behind the methods. The assumptions of LCIA methods should be coherent within conceptual framework of LCA methods. As an example, estimation of reserve value in CML is based on either economic reserves, reserve base or ultimate reserves.

2.8.3 The input parameters

The input parameters for different methods may be assessed based on different criteria, including stability, geographical representativeness, time representativeness, completeness, uncertainty and variability. In most cases, the difficulty to collect all required inputs ends in gaps and missing CFs.

2.8.4 Availability and reliability of the CFs

Covering all the resources is necessary for a comprehensive resource assessment by the LCIA indicators. This is a major concern in resource assessment, as none of reliable LCIA methodologies today provides a full coverage of various resource types. Parameters related to reliability of CF are accuracy, preciseness, being updatable, uncertainty of results and coherency with nomenclature. The relevant resources available in different methods, reflect the availability of CFs.

2.9 The scope of the thesis

The increased use of LCA has prompted companies and authorities to undertake extensive research and development work in the area of life cycle assessment. In the early LCA development stages, the life cycle method was the main topic of discussions, while LCIA methods became part of the scientific consensus discussions in a later stage and the recent years[57], [107]–[113]. In particular, resource issues are remained as one of the major concerns both as conceptual methodological developments and availability of related data to provide sufficient characterization factors for all resources.

Moreover, from the earliest developments of LCA in 1990, LCA experts discussed the issue of cradle to cradle modelling in earliest developments of LCA (known today as circular economy). Even though a lot of theoretical discussions are ongoing on the issue of circular economy, no concrete method has been proposed that cover all the issues from raw material, energy and emissions in a global approach. I believe that progress on resource issues in LCA can expand the use of LCA as one of concrete approaches to help the companies to integrate Circular Economy.

Regarding these concerns and with regards to generation and maintenance of life cycle impact assessment, this research project aims to:

- Develop LCA missing resource Characterization Factors (CFs),
- Propose new resource indicators(s) to improve the existing LCA resource assessment methods and to extend their use to all types of resources (e.g. abiotic resources),
- Test new indicators and CFs in real case studies.

The impact on resource will be evaluated from extraction of raw materials or recycling on the basis of social, economic and environmental indicators. Addressing resource depletion issues in LCA is based on three pillars of sustainable development, and gives the possibility of developing a resource depletion indicator, reflecting the challenges within a society. Such an indicator could be the subject of a proposal to UNEP/SETAC Life Cycle Initiative and the International Life Cycle Data System (European Commission) to initiate development of an international consensus.

Understanding these important new resource issues in LCA will open new insights, thus helps in developing specific strategies. In the following sections, I will present and discuss the areas of concern in current LCIA methods and more specifically the LCA resource indicators. A new structure for resource indicator is proposed and in addition a list of characterization factors is provided and tested on some resources.

3. New Rare Earth Elements resource depletion indicators for CML and ReCiPe

Highlights:

- Missing characterization factors for REEs in Life Cycle Assessment (LCA) are calculated and provided. (based on two widely used resource indicators CML and ReCiPe)
- Wide range of data is gathered for both the methods and provided in this chapter.
- Characterization Factors are tested in case of permanent magnets.
- Finally, applicability of provided CFs is validated and some cautions are provided for the practice.

3.1 Introduction

Rare Earth Elements (REEs) are critical raw materials, with high supply risk. Despite the supply risk, REEs are used more and more in products, especially those contributing to transition to green economy. In Life Cycle Assessment, REE's status is surprising and is a source of paradox. While REEs are present in numerous Life Cycle Inventory datasets, especially for electronic products, methods and indicators do not support reliable quantification of consequences of their use on depletion of resources. The main purpose of this chapter is to develop new CFs for REEs, enabling impact assessment of these resources with the most largely used European methods: CML and ReCiPe.

3.2 Rare Earth Elements context

REEs are the seventeen similar metallic elements from lanthanum to lutetium (lanthanides), also scandium and yttrium⁹. The REEs are used mainly in permanent magnets, catalysts, metal alloys, lamp phosphors, rechargeable NiMH batteries. Due to their applications, they are becoming increasingly important in transition to a green and low-carbon economy [114]–[117]. Their consumption in sectors such as transport, energy and high-tech increases both the demand and price of REEs. They are used in permanent magnets, lamp phosphors, rechargeable NiMH batteries, catalysts among other applications [114].

REEs are critical resources with strong supply risk. More than 90% of the global REEs are produced in China [114], [116]. The European Commission expert working group report (2009-2010), Defining Critical Raw Materials in the EU, identifies REEs as the most critical raw material group with the highest supply risk [100].

⁹ Pm and Sc are not included in this study, because Pm has no stable isotopes, and Sc is rarely available in the global trade of pure metals. Total transport of about 50 kilograms per year.

In addition, some direct and indirect environmental and social concerns are raised for the extraction and processing REEs [117], particularly, due to the presence of uranium and thorium [64].

The other major issue is recycling of REEs and balance problem [118]. This problem exists on the absence of primary deposits. As the demand for different REEs is not the same and REEs occur in different ratios in ores, extraction of less abundant elements increase their scarcity. Hence, recycling of REEs even for their suppliers is an important issue.

3.2.1 Rare Earth Elements resource depletion assessment in LCA

Life Cycle Assessment (LCA) is based on two steps. The first step, Life Cycle Inventory (LCI), covers identification and quantification of consumption of raw resources from earth and emissions of substances in the environment. The second step, Life Cycle Impact Assessment (LCIA) enables calculation of the impact, summing up impacts, associated with resources consumption and all emissions in the environment (cf. Chapter 1). Impact assessment is based on a variety of LCIA methods [119].

To combine and convert the LCI results to impacts, the impact characterization uses science-based conversion factors, called characterization factors (also referred to as equivalency factors). Characterization factors convert multi-scale inputs to a comparable impact indicator.

The below methods provide CFs (or metrics) for assessing resource Depletion Potential in the LCA [66], [76]:

- a) Based on reserves and/or annual extraction rates
- b) Exergy
- c) Surplus energy
- d) Marginal cost

Existing LCA impact assessment methods do not provide CFs for the REEs [64]. It means that during assessment and interpretation of LCA results, no hotspot may be identified, linked to the REE resource depletion as the flows are not characterized in the impact assessment methods. Among the LCIA methods (including ReCiPe), the only method, providing CFs for REEs was developed by Guinée and Heijungs (1995), in which wrong assumptions were made on the extraction rates of REEs [78].

In this study, two mostly used resource depletion potential methods are selected. The so-called, CML (Based on reserves and/or annual extraction rates) and ReCiPe (Additional marginal costs of extraction) methods are used as the bases to develop the CFs of REEs. In addition, this chapter proposes a framework to assess the existing LCIA resource depletion methods.

3.3 The Methods

3.3.1 The CML resource depletion potential

CML method is an LCIA method, developed by the Institute of Environmental Sciences (CML) of Leiden University [77], [78]. This method covers several impact categories, including resource depletion. CML resource depletion method is recommended by International Reference Life Cycle Data System (ILCD) [68], and is also used in Product Environmental Footprint (PEF) method [13] to assess the resources depletion potential. In this method, dimensionless Abiotic Depletion Potential (ADP) (Relation 3-1) is the annual extraction rates of a given element, divided by the squared reserve of the same element. Antimony is considered as the reference substance; therefore, the formula is normalized by antimony. So, the CFs of each resource are proportional to antimony. Results are expressed in kg Sb-eq (Antimony Equivalent).

$$ADP_i = \frac{Ext_i}{Res_i^2} \times \frac{Res_{Sb}^2}{Ext_{Sb}}$$

Relation 3-2 [77], [78]

Where, Ext_i and Res_i are respectively extraction rate and the reserve of the resource under study in the i^{th} year. Ext_{Sb_i} and Res_{Sb_i} are the same values for the reference, antimony. The larger the reserve, the less valuable the element, so ten kilogram extraction of a resource has different depletion impacts in the two cases of a large or a small reserve. The estimation of the reserve value can be based on two different assumptions:

- Guinée et al. (2002) used the ultimate reserves; i.e. the resource quantity, which is available in the earth's crust. It is approximated by multiplying the average natural concentration of the resources in the earth's crust by the mass of the crust.
- Oers et al. (2002) proposed the economic reserves, reserve base and ultimate reserves. The reserve base includes all the deposits that meet certain minimal chemical and physical requirements to be potentially economic to be exploited.

Both approaches are considered here. Each approach has some advantages and disadvantages: The ultimate resource base is a relatively robust reference with low uncertainty, but its environmental relevance seems limited. On the other hand, the economic reserves, which is more uncertain, is more representative of today's available resources. These two extremes (ultimate and economic reserves) can be used as guides to assess the severity of the impacts, associated with the use of a resource. The approach, which is used in this study, is based on Oers et al. (2002). (Results provided for economic reserves in this work but also assessed for reserve base and ultimate reserves.)

3.3.2 ReCiPe methodology

In LCA, the “damage” is sometime defined as the additional costs that the society has to pay as the result of extraction. This approach is used in the ReCiPe method where the cost of the resource extraction is calculated with the marginal cost increase of a resource during a certain period of time or a quantity of extracted resource. This could be the

annual production of a resource in a global scale, or the apparent consumption of a resource within a specific region [84].

The CFs are expressed as Surplus Cost. These are the costs, incurred due to the fact that after extraction of some part of a resource with the highest grade, future mining would become more expensive. The results are also expressed in relative impact but the CFs are normalized by iron (instead of antimony). The values are given in kg Fe-eq (iron equivalent).

- The impacts are based on the increase of the cost of resource extraction. However, the consequences of this cost-increase (shift toward unconventional resources and alternatives) are not taken into account.
- Available resources are supposed to be extracted in an organized program, i.e. higher concentration ore bodies are extracted first.

3.3.3 Existing characterization factors

Based on available observations, limited number of characterisation factors for resource depletion are available. For the two methods, the number of available CFs for different types of resources are provided in Table 3-1 [76].

Table 3-1 Number of natural resources, covered by CML and ReCiPe.

	CML 2002 (van Oers et al. 2002)	ReCiPe (Goedkoop et al. 2009)
Abiotic minerals	48	19
Abiotic energy: fossil and nuclear	5	5

3.3.3.1 CML method and REEs

The only resource depletion CFs for the REEs, named CML, were developed by Guinée and Heijungs (1995) [77]. The CFs from CML method are obtained based on the

extraction rates, provided by the USGS reports. As the extraction rates of REEs are not available in the USGS reports for REEs [120], Guinée and Heijungs (1995) assumed that the extraction rates for all the REEs is equals to the extraction rate of rhenium [78]. This assumption resulted in imprecise CFs in the 1995 REEs CML report [77]. If the 2014 mine production is compared for REEs and the rhenium [120], the REEs production is three times higher than the rate of rhenium. This is the main reason why during the revision of CML in 2002 [78], the 1995 CFs are excluded for REEs¹⁰ (Oers et al. 2002).

3.3.3.2 ReCiPe method and REEs

The development of CFs for the ReCiPe method was done for 20 elements. The list of elements does not include REEs [84]. Nonetheless, the authors did not find any published work about the CFs of the REEs.

3.4 Filling the gap of characterization factors for both the methods

3.4.1 Background data collected in this study

CFs are developed in this chapter for the two mentioned methods, based on the existing data from different available references. Part of information is extracted from the USGS 2013 and 2014 archive [120]. Additional information is collected from specific mining reports. The development is done for 11 giant deposits world-wide (Table 3-2). The amount of REE differs from a deposit to the other, in different geographical situations. Availability of REEs in different commodities is reported in Table 3-3.

¹⁰ Compared to the set of factors, Guinée (1995), some elements are missed in the updated version (2002): Actinium, Argon, Cerium, Cesium, Dysprosium, Erbium, Europium, Gadolinium, Hafnium, Holmium, Krypton, Lanthanum, Lutetium, Neodymium, Neon, Polonium, Praseodymium, Protactinium, Radium, Radon, Rubidium, Samarium, Scandium, Terbium, Thorium, Thulium, Xenon and Ytterbium (Oers et al. 2002).

Table 3-2 Specifications of giant deposits, used in the case study.

TREO: Total Rare Earth Oxide E.g. TREO=25% means that RE in the form of oxides becomes 25% of the original. **OPEX:** operating expenditure, are the current costs to operate a mine. **CAPEX:** capital investment expenditure, referring to the cost of development or supplies and non-consumable parts for the product or system of the mine. **Measured resource:** the estimated quantity and grade of that part of a deposit of which the size and grade configuration is well-established by observations and samplings on the outcrops, drilled holes, trenches and mine workings. **Indicated resource:** the estimated quantity and grade of part of a deposit of which the continuity of grade, together with the extent and shape, are well-established, so a reliable grade and tonnage estimation can be figured out. **Inferred resource:** this part of the resource is determined by limited sampling, but there is sufficient geological information and reasonable understanding of the continuity and distribution of metal bodies to outline that part as a potentially economic merit. ** Non-operational mines (in 2013). * Data not available, average value for other deposits is used as proxy.

		Total Reserve: indicated and inferred (Mt)	Average grade of TREO (in percentage)	Total REO Reserve base (Mt)	Predicted Total REO production (t)	OPEX (\$/kg)- mining cost	CAPEX (US-\$-M)- mining cost	Total Mining cost (CAPEX), over 10 years (US-\$)	Host Rock
Mountain Pass	USA	47	8.90	18.40	18000	2.7	1420	3.77	Carbonatite
Bayan Obo (Baotou)	China	800	6.00	48.00	55000	5.6	962*	5.74	Carbonatite
Strange Lake (Lac Brisson)	Canada	492	0.90	278.13	13650	0.5	2309	0.51	Alkalic igneous
Kvanefjeld	Greenland	437	1.09	10.33	10069**	6.0	810	6.00	Alkalic igneous
Lovozero	Russia	1000	0.01	15.00	12000	6.4	962*	9.83	Alkalic igneous
Mount Weld	Australia	24	7.71	0.37	11000	12.1	907	12.16	Carbonatite
Nolans Bore	Australia	25	2.72	0.67	22000	7.0	1408	7.00	Carbonatite
Zandkopsdrift	South Africa	23	2.32	0.95	20000**	13.0	1760	13.08	Carbonatite
Bear Lodge	USA	3	3.77	0.56	13000**	7.0	404	6.55	Carbonatite
Ngualla	Tanzania	175	2.32	0.94	10069	12.0	367	11.74	Carbonatite
Norra karr	Sweden	42	0.57	0.34	8000	11.0	266	10.93	Alkalic igneous

Table 3-3 The availability of REEs in different commodities.

The unit is in the percentage. Note that for Brockman, production and reserve data are not available. Other commodities like (Fe - Nb2O5 - Ta2O5 - ZrO - BeO - U3O8 - Zn - P2O5) are produced in the mentioned mines also; but are not imported in calculations.

	LREO %				HREO %										
	Lanthanum	Cerium	Praseodymium	Neodymium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium	Yttrium
Mountain Pass	33.50	49.35	4.20	11.60	0.85	0.11	0.19	-	-	-	-	-	-	-	1.35
Bayan Obo (Baotou)	24.00	50.00	5.65	17.60	1.00	0.20	0.70	0.1	0.10	-	-	-	-	-	0.10
Strange Lake (Lac Brisson)	13.20	30.62	3.33	12.00	1.95	0.14	2.70	0.55	3.64	0.78	2.34	0.33	1.82	0.24	24.80
Brockman	5.80	16.80	0.10	0.40	0.03	-	0.40	0.1	10.4	0.20	7.70	0.10	5.00	0.10	52.40
Kvanefjeld	27.90	37.15	4.57	13.42	2.92	0.20	1.76	0.31	1.36	0.23	0.60	0.07	0.30	0.02	9.89
Lovozero	28.00	57.50	3.80	8.80	0.96	0.13	0.21	0.07	0.09	0.03	0.07	-	0.29	0.05	-
Mount Weld	25.50	46.74	5.32	18.50	2.27	0.44	-	0.07	0.12	-	0.03	-	0.06	-	0.35
Nolans Bore	19.74	47.53	5.82	21.20	2.37	0.40	1.00	0.08	0.33	0.05	0.09	0.01	0.05	0.01	1.32
Zandkopsdrift	25.42	44.17	4.55	15.77	2.31	0.59	1.44	0.17	0.77	0.15	0.15	0.15	0.15	0.15	4.07
Bear Lodge	30.40	45.50	4.70	15.80	1.80	0.40	0.70	0.1	0.20	-	-	0.01	0.5	0.01	1.11
Ngualla	27.10	48.30	4.70	16.30	1.70	0.35	0.78	0.07	0.17	-	-	-	-	-	0.52
Norra karr	8.46	18.04	2.31	9.13	2.89	0.38	3.66	-	5.34	-	3.95	-	4.25	0.67	40.93

3.4.1.1 Prices of Rare Earth Elements and iron, used in ReCiPe method

The prices of the REEs and iron are the base information to make the calculations in the ReCiPe method. The REEs were subject to significant price fluctuations due to the geopolitical issues, related to the china export quotas on REEs in the recent five years. The prices are more stable and better reflect the scarcity of the REEs when the 2013 situation is considered (Table 3-4). The recommended REEs CFs for ReCiPe in this chapter are the one derived from the 2013 prices. The CFs based on the REEs average price within five years from 2009 to 2013 in kg Fe-eq are provided in Appendix 1.

3.4.2 Characterization Factors of Rare Earth Elements by CML

Using the extraction data of different mines and the grade of REEs in different commodities, we calculate the extraction rate (mineral production) and the reserves (from indicated and inferred resources) for the REEs. To compare our results with the ReCiPe method, the results are converted to Fe-eq as a reference, following the approach to calculate the Sb-eq (Table 3-4).

Table 3-4 The CFs of REEs, developed based on the CML method (Fe-eq / Sb-eq)

	Mine extraction (production) (ton)	Total economic reserve (ton)	$\frac{\text{Extraction rate } i}{(\text{reserves } i)^2}$	Depletion Fe-eq 2013	Depletion Sb-eq 1999
Sb 1999	1.38E+05	3.20E+06	1.35E-08		1.00E+00
Fe 2013	2.95E+09	8.10E+10	4.50E-13	1.00E+00	
La	4.71E+04	1.55E+07	1.96E-10	4.36E+02	1.45E-02
Ce	8.79E+04	3.05E+07	9.44E-11	2.10E+02	7.01E-03
Pr	9.25E+03	3.14E+06	9.36E-10	2.08E+03	6.95E-02
Nd	2.99E+04	9.60E+06	3.24E-10	7.21E+02	2.40E-02
Sm	3.22E+03	8.06E+05	4.95E-09	1.10E+04	3.67E-01
Eu	5.51E+02	1.29E+05	3.30E-08	7.33E+04	2.45E+00
Gd	1.94E+03	4.85E+05	8.25E-09	1.84E+04	6.12E-01
Tb	2.47E+02	7.77E+04	4.10E-08	9.11E+04	3.04E+00
Dy	1.40E+03	2.34E+05	2.55E-08	5.68E+04	1.89E+00
Ho	1.73E+02	3.53E+04	1.39E-07	3.08E+05	1.03E+01
Er	7.55E+02	1.09E+05	6.35E-08	1.41E+05	4.72E+00

Tm	8.50E+01	1.28E+04	5.22E-07	1.16E+06	3.87E+01
Yb	7.65E+02	1.04E+05	7.04E-08	1.56E+05	5.22E+00
Lu	1.27E+02	1.46E+04	5.94E-07	1.32E+06	4.41E+01
Y	9.29E+03	1.34E+06	5.21E-09	1.16E+04	3.86E-01

3.4.3 Characterization Factors of Rare Earth Elements by ReCiPe

The below steps [84] are followed to develop the CFs for REEs based on the ReCiPe method:

Step 1: Low weighted grade value if the weighted yield value increases.

Weighted grade Value of mine m (\$/kg): $g_{v,m} = \sum (g_{c,m} \cdot V_c)$

$g_{c,m}$: grade of commodity c at mine m.

V_c : market value of commodity c (\$/kg).

Weighted yield Value of mine m (\$): $Y_{v,m} = \sum (Y_{c,m} \cdot V_c)$

$Y_{c,m}$: yield of commodity c at mine m (kg).

Values of $g_{c,m}$ and $Y_{c,m}$ are plotted in the same graph for each alkali igneous and carbonatite hosts (Figure 3-1).

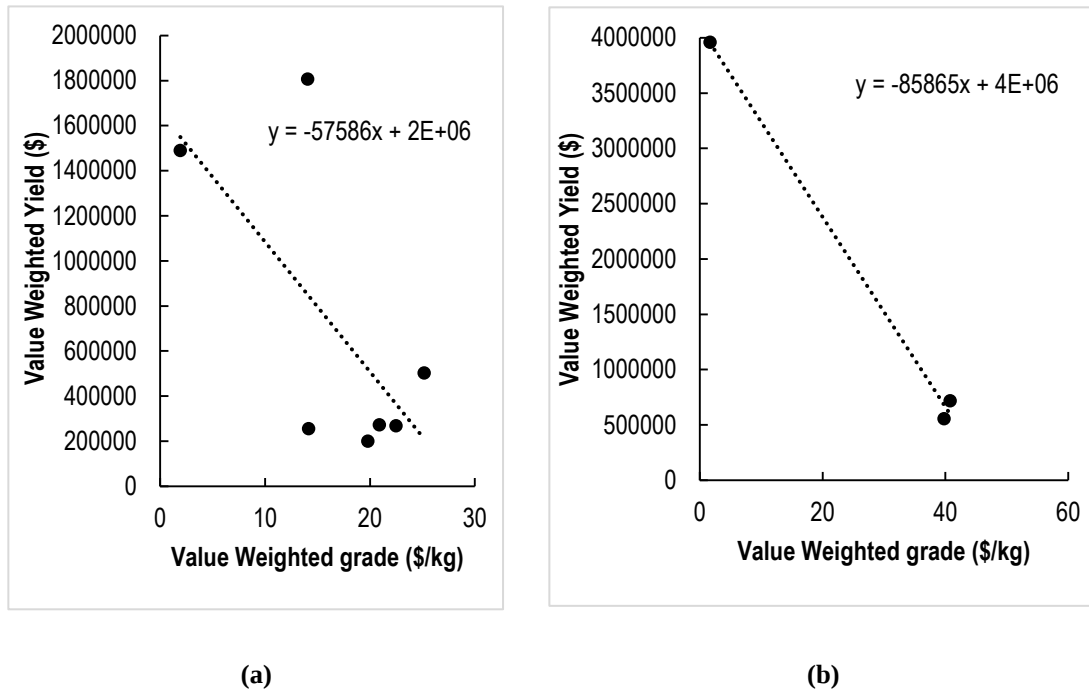


Figure 3-1 Cross-plots of weighted yield values and grade for a) carbonatites and b) alkali igneous rocks.

Certain amount of extraction (\$) will cause a certain change in the weighted grade value (\$/kg), determined by the slope M_d (kg) and the constant C_d (\$). For each deposit, we can write:

$$Y_{v,d} = M_d \times g_{v,d} + C_d \quad \text{Relation 3-3 [84]}$$

Where $Y_{v,d}$ is the cumulative weighted yield value, over all mines of deposit d (\$), $g_{v,d}$ is the weighted grade value of deposit d (\$/kg), and M_d is the slope (kg), while C_d is a constant, in \$.

The M_d for carbonatite and alkalic igneous is respectively -57'586 and -85'865. The obtained C_d for carbonatite and alkalic igneous is respectively 2000'000 and 4000'000.

Step 2: from the weighted grade value to the marginal cost increase. (Figure 3-2)

The cost to mine a certain amount of ore of deposit d (\$/\$):

$$C_{d,\$} = \frac{1}{g_{v,d}}$$

Relation 3-4 [84]

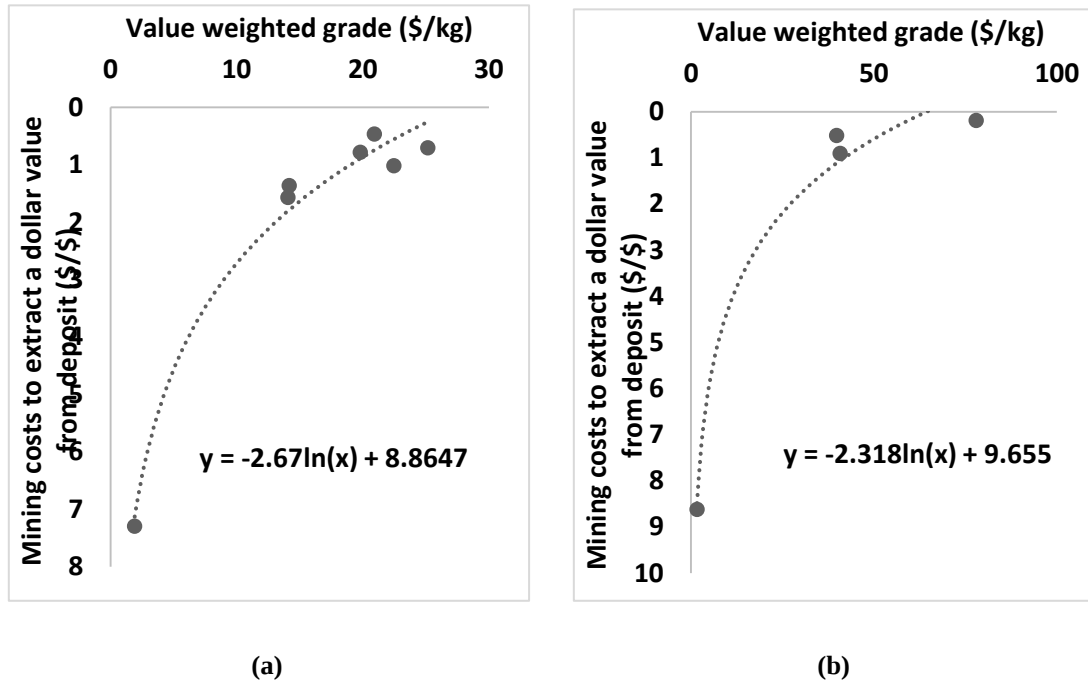


Figure 3-2 Grade-cost relation in mines for a) carbonatites and b) Alkali igneous.

Step 3: Calculating the Marginal Cost Increase (MCI) on deposit level.

$$MCI_{d,\$} = \frac{\partial C_{d,\$}}{\partial Y_{v,d}} = \frac{\partial C_{d,\$}}{\partial g_{v,d}} \times \frac{\partial g_{v,d}}{\partial Y_{v,d}} = -\frac{xM_d^2}{(-0.5c_d)^2} \times \frac{1}{M_d} = -4x \times \frac{M_d}{(c_d)^2}$$

Relation 3-5 [84]

$$CF_{d,\$} = MCI_{d,\$} \times P_{d,\$} \times NPV_T = -4x \times \frac{\bar{M}_d}{(\bar{c}_d)^2} \times P_{d,\$} \times NPV_T$$

Relation 3-6 [84]

$MCI_{d,\$}$: the marginal cost increase on the deposit level (1/\$).

$P_{c,\$}$: the amount of deposit d , in \$/yr.

NPV_T: net present value factor (yr).

Units of the characterization factor CF_{d,\$} on this level is \$/\$.

Step 4: From marginal cost increase on deposit level to cost increase on commodity level.

$$\bar{M}_c = \frac{\sum_d (Y_{c,d} \times M_d)}{\sum_d Y_{c,d}} \quad \text{and} \quad \bar{C}_c = \frac{\sum_d (Y_{c,d} \times C_d)}{\sum_d Y_{c,d}} \quad \text{Relation 3-7 [84]}$$

M_c and C_c are respectively the slope and constant on deposit level, recalculated to commodity level c.

Step 5: From marginal cost increase per dollar to a characterization factor per dollar.

Calculating the mid- point characterization factors, by marginal cost increase per dollar:

$$CF_{c.kg.mid} = -\frac{\bar{M}_c}{(c_c)^2} \times V_c^2 \times P_{c.kg} \quad \text{Relation 3-8 [84]}$$

The Table 3-5 reveals the results of the calculations. The mid-point CFs and Fe equivalent are calculated, using different values of V_c (2013). The results show the importance of taking into consideration the variation of metal price. ReCiPe method end-point characterization factors are provided in Appendix 3.

Table 3-5 ReCiPe Characterization Factors (CFs) of REEs, using 2013 prices.

Vc (2013)								
	Mc (average)	Cc (average)	Vc 2013	Vc (avg5 yrs)	Pckg	Midpoint	Fe eq	
LREO	Lanthanum	-62820	2370162	3.71	42.65	4.71E+04	7.26E-03	1.76E-01
	Cerium	-62831	2370921	3.96	43.35	8.79E+04	1.54E-02	3.73E-01
	Praseodymium	-62334	2335786	94.08	92.80	9.25E+03	9.35E-01	2.26E+01
	Neodymium	-62084	2318146	52.81	101.48	2.99E+04	9.64E-01	2.33E+01
	Samarium	-65492	2559166	3.05	51.83	3.22E+03	3.00E-04	7.26E-03
HREO	Europium	-61909	2305772	759.22	1711.50	5.51E+02	3.70E+00	8.95E+01
	Gadolinium	-70081	2883695	27.32	75.93	1.94E+03	1.22E-02	2.96E-01
	Terbium	-70659	2924541	561.16	1536.25	2.47E+02	6.44E-01	1.56E+01
	Dysprosium	-79120	3522958	288.83	757.25	1.40E+03	7.46E-01	1.81E+01
	Holmium	-79318	3536939	180.40	2623.33	1.73E+02	3.57E-02	8.64E-01
	Erbium	-83907	3861547	180.40	165.87	7.55E+02	1.38E-01	3.35E+00
	Thulium	-74966	3229187	180.40	3986.00	8.50E+01	1.99E-02	4.82E-01
	Ytterbium	-81765	3710043	180.40	293.80	7.65E+02	1.48E-01	3.58E+00
	Lutetium	-78555	3482980	180.40	3026.67	1.27E+02	2.68E-02	6.50E-01
	Yttrium	-80917	3650039	9.90	69.33	9.29E+03	5.54E-03	1.34E-01
	Fe			0.27	0.27	8.50E+11	4.13E-02	1.00E+00

3.5 Discussion

3.5.1 Requirements of resource depletion Characterization Factors

Existing LCIA methods for resource assessment are assessed here from different viewpoints. The assessment is conducted at different levels: (i) a conceptual framework, (ii) the basic assumptions, (iii) input parameters and (iv) availability and reliability of CF.

3.5.1.1 A conceptual framework

A conceptual framework is considered as the first criterion of resource assessment methods and reflects the comprehensiveness of methods to answer the resource problem. The indicator compares the goal of resource assessment, defined in different methods with resource related challenges, society is facing.

With regard to a conceptual framework, existing LCA methods are either based on inherent properties and depletion of materials, or based on prediction of future extraction efforts [91]. The challenges, which the society is facing, are not reflected correctly in neither CML nor ReCiPe method. Both methods consider the accessibility to geological reserves. The corrected accessibility through recycling, and the anthropogenic stock is not part of the models.

In addition, the methods do not provide a conceptual framework to assess all types of resources. This issue is usually associated with some considerations, behind the LCIA methods and some efforts are needed to develop new CFs. Only the extraction rate and the available reserve are considered in CML method, while regeneration rate (related to the biogenic resources) is neglected. ReCiPe method does not provide any baseline to assess biotic resources.

3.5.1.2 The basic Assumptions

Different assumptions, theory and background exist behind the methods. The assumptions of LCIA methods should be coherent within conceptual framework of LCA methods. As an example, estimation of reserve value in CML is based on either economic reserves, reserve base or ultimate reserves.

The first assumption in this study is extraction allocation to individual REEs. Extraction allocation means the ratio of which each element (here REEs) are extracted as co-product of extraction (Table 3-3). A mass based allocation is applied based on the values provided in Table 3-3. The values in Table 3-3 include some uncertainties, related to geologic and exploration reports. The fact that more than 80% of REEs resources are covered in this study makes the results much more reliable.

Another major assumption is the choice of REEs prices, used in ReCiPe. REEs were subject to significant price fluctuations due to the last five-year geopolitical issues, related to china export quotas on REEs. Extremely high fluctuations of REEs prices affects the CFs. The REEs prices in 2013 are selected, as they are more reliable and more stable, compared to the last five years average prices.

3.5.1.3 The input parameters

The input parameters for different methods are assessed based on different criteria, including stability, geographical representativeness, time representativeness, completeness, uncertainty and variability. In most cases, the difficulty to collect all required inputs ends in gaps and missing CFs.

Regarding the geographical representativeness, the data used in the present study are obtained from mining reports, corresponding to specified geographical zones. Time representativeness is very high as the data is gathered for 2013. An issue is the comparability of the new CFs to non-updated CML base-line CFs (since 2000).

In the case of CML, the extraction rates from one side and the economic reserves (or reserve base or ultimate reserves) from the other side are required. For most of metal resources, the data could be obtained from USGS database. For resources that data is insufficient, like REEs, it is needed to collect them from other sources or to consider some assumptions. For REEs, the main difficulty is the extraction rate. Finally, covering more than 80% of worldwide resources guarantees completeness of the results.

Availability of most of active mines enables us to have a reliable dataset. Nevertheless, the extraction is either predicted or derived from mining reports, which are sometimes uncertain; and there are high fluctuations due to supply restrictions in the recent years. In addition, closing and reopening several REE mines have amplified extraction fluctuations.

For ReCiPe, the complexity is higher as more data and data sources are needed, including the cost of mining and REE Prices (Table 3-2 and 3-3). Regarding mining costs, it is very difficult and in some cases impossible to have a reliable mining costs. As an example, CAPEX for Bayan Obo (Baotou) in China is not available in mining reports. Another major issue is regarding REEs prices, used in ReCiPe. Extremely high fluctuations of REEs prices within the past years, affects reliability of prices also. This is also the reason why a sensitivity analysis is done here, considering REEs prices in 2013, compared to the average price within five years (2009 -2013) and is provided in Appendix 1.

3.5.1.4 Availability and reliability of the CFs

Covering all the resources is necessary for a comprehensive resource assessment by the LCIA indicators. This is a major concern in resource assessment, as none of reliable LCIA methodologies today provides a full coverage of various resource types. Parameters related to reliability of CF are accuracy, preciseness, being updatable, uncertainty of results and coherency with nomenclature. The relevant resources available in different methods, reflect the availability of CFs.

The main parameter influencing the existence of CFs is the efforts needed to develop new CF. This is well reflected when comparing CML and ReCiPe. ReCiPe requires a set of data that is more exhaustive, therefore the available CFs are around three times lower than CML method.

Completeness, variability and uncertainty of inputs play significant roles on preciseness of the CFs. In the case of holmium, erbium, thulium and ytterbium, the very low presence in deposits and the very low extraction rates result in highly unreliable values. Regarding the prices, "Vc" is not available for these four elements, and the average of other REEs is considered instead. That is why I notice cautions when using CFs for holmium, erbium, thulium and ytterbium.

3.5.2 Comparison of CFs, derived from CML and ReCiPe

The REEs are among the resources with relatively high resource depletion impact (Figure 3-3), therefore important to be included in the resource impact assessment methods. If we consider the CML, the highest CFs values are allocated to the gold, tellurium and platinum (52, 40.7 and 2.22 Sb eq, respectively) and the lowest values belong to the silicon and aluminum ($1.4\text{E-}11$ and $1.9\text{E-}9$ Sb eq, respectively). For ReCiPe (before including the REEs), the highest value corresponds to platinum, gold, rhodium (163000, 69900 and 20300 Fe eq, respectively) and the lowest are aluminum and iron (0.0901 and 1 Fe eq, respectively). Note that based on the obtained results, the REEs are placed in the middle of the resources for ReCiPe and with high impact in CML. As an example, neodymium is $2.40\text{E-}02$ Sb eq for the CML and $2.33\text{E+}01$ for ReCiPe.

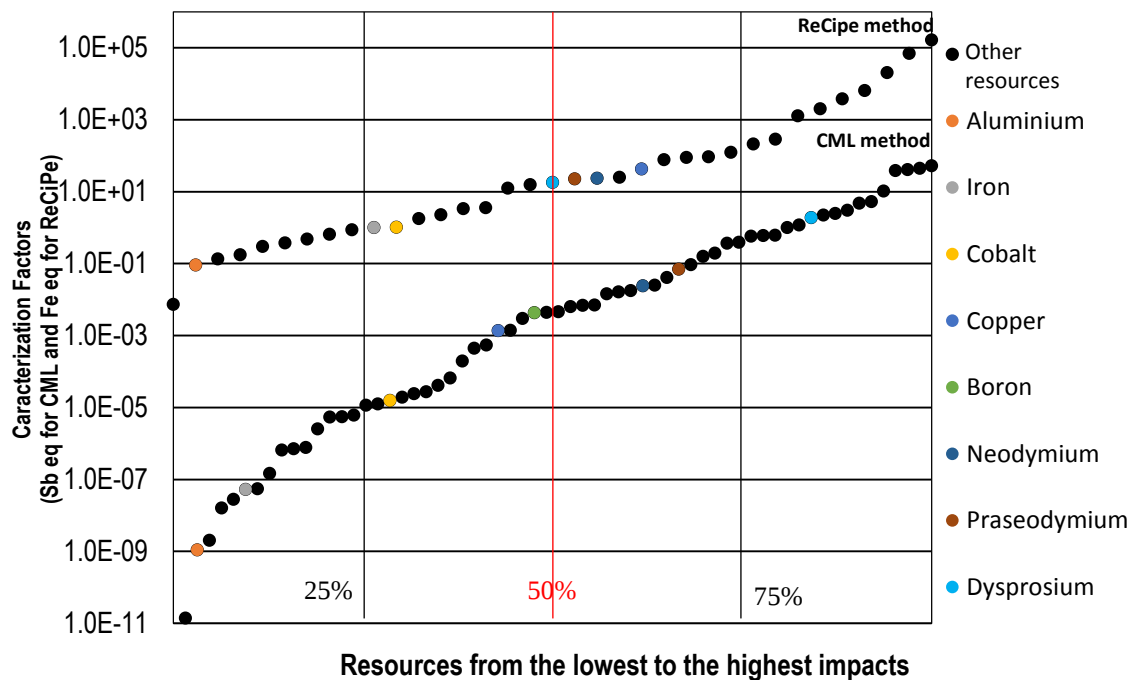


Figure 3-3 The CFs, in CML and ReCiPe methods, using 2013 REEs prices, ranked from the lowest to the highest impacts for each method
 Figure represents the existing CFs for the 35 substances for ReCiPe and the 63 substances for CML – including 15 REEs CFs, developed in this study – 8 substances are highlighted in the figure – Boron CF is not available in the ReCiPe method.

The Figure 3-3 illustrates the high variation of CML factors (logarithmic scale), from the lowest to the highest compared to the ReCiPe method. Number of available Characterization Factors are higher for CML compared to ReCiPe (35 and 63 substances, respectively). Red line represents in the median (50%) for both the methods. Considering the first tier in Figure 3-3, no critical resources is highlighted. Resources like cobalt and copper with high supply risk are placed in the lower middle (for both the methods and for CML, respectively), confirming the fact that the conceptual framework of the two methods are not reflecting the resource challenges, which the society is facing. All REEs, except dysprosium for the CML method are placed in the third tier of the figure, highlighting the fact that these resources are not with the highest depletion factors. While using high amount of these elements may generate high resource depletion impacts. The

REEs, present in the second tier is the dysprosium when CML is applied, representing the most critical REE.

3.6 Case study on NdFeB permanent magnets

In this part, the obtained results of the REEs characterization factors are tested in a real case for NdFeB permanent magnets with high REE contents.

3.6.1 NdFeB permanent magnet

Physical properties of REEs make them ideal for permanent-magnet alloys. Their high spin-orbit coupling, results in magnetocrystalline anisotropy, which leads to high values of coercivity [121]. NdFeB magnets contains magnetically hard phase based on (Nd,Pr,Dy)–Fe–B and other trace elements, with a variety of REEs and Fe contents. REE contents of magnets vary from 27 to 32 wt.%, Fe ranging from 50 to 73 wt.%, B at 1 wt.% [122], and other minor additions of transition metals. The magnet, assessed in this case-study is composed of, 32% Nd, 66% Fe, 1% B, 0.29% Dy, 0.04% Al, 0.01% Cu, 0.08% Co and 0.57% Pr.

The inventory, used for LCA modelling of permanent magnet is derived from its energy consumption [121], and completed by specific industry data from China.

3.6.2 NdFeB permanent magnet inventory

The assessment is conducted for production of 1 kg of the cradle to gate NdFeB permanent magnets. The losses (27%) for all processes from the mining to the final production are included in the assessment. Particles are emitted during the production process and are considered in the inventory. The inventory is cradle to gate and the downstream processes (E.g. End of Life) is not considered. Detailed inventory is provided in Appendix 2.

Table 3-6 provides life cycle inventory of raw materials inputs for which a CF is available in CML baseline and the ReCiPe method to which the flows of the REEs are added. Table 3-6 also provides the characterized results for the resource based on the two impact assessment methods, including and not including the REEs, calculated based on the CF, developed in this study.

Table 3-6 Inventory of resource inputs for 1 kg of the permanent magnet cradle to gate / impact of resource based in CML and ReCiPe methods

Substances	Total mass	Unit	ReCiPe (Fe eq)	ReCiPe including REs CFs	CML (Sb eq)	CML including REs CFs
Iron	1.25E+00	kg	1.25E+00	1.25E+00	6.54E-08	6.54E-08
Neodymium	4.09E-01	kg		9.54E+00		9.83E-03
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	1.11E-02	kg	4.72E-01	4.72E-01	1.51E-05	1.51E-05
Nickel, 1.98% in silicates, 1.04% in crude ore	1.93E-02	kg	2.41E-01	2.41E-01	1.26E-06	1.26E-06
Chromium	8.11E-03	kg	2.02E-01	2.02E-01	3.59E-06	3.59E-06
Praseodymium	7.29E-03	kg		1.65E-01		5.07E-04
Manganese	9.81E-04	kg	7.51E-02	7.51E-02	2.49E-09	2.49E-09
Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore	2.38E-03	kg	1.02E-01	1.02E-01	3.26E-06	3.26E-06
Cadmium	1.02E-04	kg			1.59E-05	1.59E-05
Lead	1.69E-03	kg	3.00E-03	3.00E-03	1.07E-05	1.07E-05
Dysprosium	3.76E-03	kg		6.80E-02		7.11E-03
Other			4.65E-01	4.65E-01	7.04E-05	7.04E-05

As shown in Figure 3-4, significant differences are highlighted when the REEs factors are included. The difference is less substantial in ReCiPe based method (ReCiPe with REEs CFs is almost twice higher) due to relatively high CF for iron, compared to the CML-based method. For the CML-based method, the impacts are almost 100% from the presence of the REEs in the magnet. The results (Figure 3-4) show the importance of

including the REE characterization factors to help the correct interpretation of the LCA results, especially when a product contains significant content of REEs.

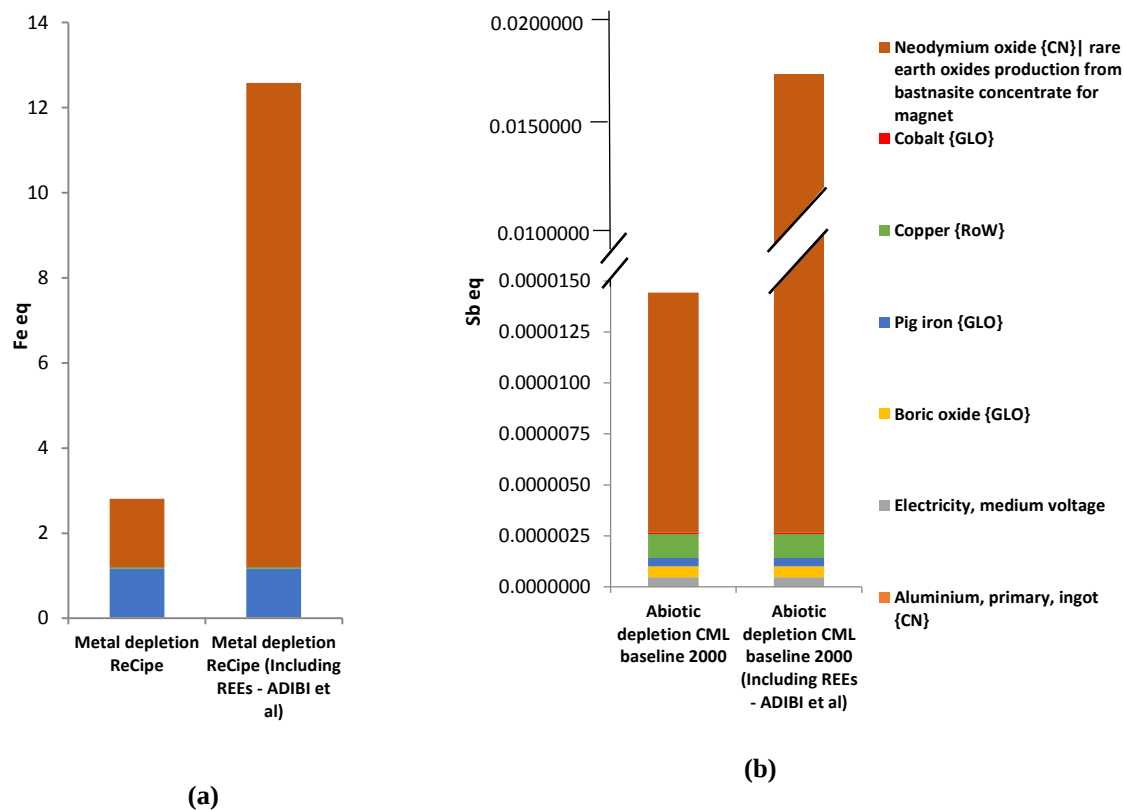


Figure 3-4 Resource impact assessment contribution analysis for ReCiPe (right) and CML baseline (left) with and without REs CFs of 1 kg of permanent magnet NdFeB (32%/66%/1%) cradle to gate.

REEs are major elements in the magnets. 32% of the composition of the studied magnet is neodymium. The mass of the Neodymium is 409 grams, including the losses during the production phases. Other major inputs are Fe, representing 66% of the magnet composition. In addition, the energy consumption is one of the major inputs for the magnet production.

Due to both the CML and ReCiPe methods, the REEs have the highest impact, compared to other resources, included in the magnets (Figure 3-4). In the CML method,

the neodymium is responsible for more than 99% of the impacts. As shown in Figure 3-4, the high mass of iron with a relative high impact in the ReCiPe method (compared to the CML) represents around 10% of the final impacts while the neodymium is largely dominant with more than 80% of the impact. Except the pig iron, other inputs do not represent impacts regarding the resource depletion for both the CML and ReCiPe methods. The results (Figure 3-4) confirm the importance of including REE CFs in the impact assessment calculations.

The NdFeB (32%/66%/1%) cradle to gate inventory is provided as supporting information in appendix 2. Finally, it is necessary to highlight the need for checking and in some cases correcting the inventory in available generic LCA databases, before using the calculated CFs.

3.7 Conclusions

This study provides, for the first time, the resource depletion characterization factors for very strategic REEs resources based on two widely-used LCA impact assessment methodologies in Europe, i.e. CML and ReCiPe. These CFs are useful to be implemented in the main LCA software such as Simapro and GaBi in order to be able to address the issue of the resource depletion of the REEs.

REEs are among resources with a relatively high resource depletion potential, therefore with high importance to be included in the assessment of resources depletion impact. Using the CFs in analyzing NdFeB permanent magnets in this study showed that the CFs of the REEs have significant effect on the LCA resource impacts of the products. In addition, the applicability of the provided CFs is checked by the NdFeB permanent magnets case study.

Four additional conclusions from this study:

1. The difficulties and wide range of data needed to develop the missing additional characterization factors is well illustrated. The missing data (or difficulty to find the

corresponding data) leads to the fact that several gaps can be identified in the available resource assessment methods. The existing gaps and differences in characterization methods lead to the fact that no method covers all the resources. This problem rises in some highly strategic resources, including Rare Earth Elements (REEs).

2. Covering all the resource types is necessary for a comprehensive resource assessment by LCIA indicators. This is a major issue in resource assessment by LCA today, as none of reliable LCIA methodologies (including CML and ReCiPe) provides full coverage of different resource types.
3. This issue is associated with the concepts behind the LCIA methods. The methods are not developed to be used for all types of the resources, and no CF provides precise interpretations in all the cases. As in the CML method, only the extraction rate of a resource and the available reserve are considered, while regeneration rate (related to the biogenic resources) is overwhelmed.
4. In this study, we developed characterization factors of REE resources following the CML and ReCiPe, two existing LCA resource depletion impact assessment methodologies. The characterization factors are then applied to the NdFeB permanent magnets. The significant difference between the results including the CFs and the baseline highlights the possible misinterpretation of results, using the current available CFs.

In addition, the concepts behind different resource depletion characterization methods need to be revised. Given the fact the resource assessment in LCA are based on the geological availability (e.g. CML and ReCiPe), the current work suggests that there is a need to go beyond the current LCIA method in order to incorporate other important factors (e.g. recycling) not yet covered by the LCA resource assessment methods. It is also important to address anthropogenic stock as the complement of the geological availability.

Ignoring recycling the metals and minerals in the current models, leads to the underestimation of the total available substance. The ratio of recycling to the available

End-of-Life stock is like the ratio of extraction rate to the resource. Within the context of LCA, further development of the impact assessment methods is necessary to cover the recycling effectively.

Considering the average five-year price of the REEs, no correlation between the CML- and ReCiPe-based methods is identified. The price V_c plays an important role in CF calculation by the ReCiPe-based method. When the 2013 price is taken into consideration, the correlation seems to be more significant; nevertheless, the fluctuation of the prices makes the characterization factors, then the impact assessment results very unstable. CFs are a clear step forward nevertheless further improvements on a few less common REEs (holmium, erbium, thulium, ytterbium, and lutetium) is recommended (i.e. the price, extraction rate and reserve availability).

Concerns over the resources rise as the demand increases. Different methodological approaches, under the LCA framework have been used so far to address the impact of resource extraction. However, they lack consistency, as available models do not address the same parameters: short vs long term, stock vs backup technology, etc. The novelty of this work could be a model for developing other methods for calculating resource depletion CFs.

4. Global Resource Indicator for Life Cycle Impact

Assessment: applied in wind turbine case study

Highlights:

- New resource impact assessment Global Resource Indicator is proposed in this chapter.
- Recyclability and criticality of resources are part of the method complementing scarcity.
- Application of Characterization Factors in the wind turbines and assessment of the results is provided.

4.1 Introduction

Increase in resource demand raises concerns over their availability. In the recent years, national and international institutions[123]–[126] have targeted sustainable resource supply and circular economy as a core goal of their short- and long- term strategies. Efficient resource consumption and production patterns are promoted by local, regional and global actors in developed and developing countries.

4.1.1 Resources Life Cycle Impact Assessment

Considering different life cycle stages of a product, Life Cycle Assessment (LCA) can be used as a decision making tool to support the transition to new economic models, including circular economy and in providing a systematic environmental assessment approach of a product, a service or a process. The weakness of LCA in this context is the debatable resource indicator. The environmental impacts, associated with the use of resources, minerals, metals, etc. in Life Cycle Assessment (LCA) framework are categorized and criticized by several authors [68], [86]–[90], [98].

These methods provide partial vision, based on limited available data, and do not reflect all the aspects related to different resources. The conceptual problems in the existing indicators limits the coverage of the resource type significantly. Few methods cover the renewable rates for biotic resources. Some critical resources like Rare Earth Elements [64], [65] are not covered by ant existing LCA resource assessment methods.

The conceptual problems in the existing methods limits the coverage of the resource type significantly. Vast coverage of an LCIA indicator is a requirement for a comprehensive resource assessment. None of reliable LCIA methodologies provide full coverage over various resource types. Few methods cover the renewable rates for biotic resources. Some others, do not cover the energy resources. No distinction is made between fossil resources, being burnt in energy consumption or used for the non-energy purposes, e.g. plastics. In most cases, even when CFs are available, they are not

comparable with different resource types, e.g. renewables versus non-renewable resources.

One of the major issues, related to the resource assessment, is that the resources inaccessibility is influential, and may even halt the development of sustainable products and services. Therefore, this chapter aims at assessing the accessibility of the resources, including the recyclability and geopolitical availability (criticality). Several valuable works have been already conducted in the context of LCA to include different aspects of resource problems. The new method proposed in this chapter is based on several aspects of the material circulation during its life cycles: Recyclability, criticality and geopolitical availability of resources are part of the method. The new approach enlarges and include the extent possible different resource assessment related criteria in a comprehensive and coherent framework. The cause and effect chain for four main groups of resource assessment indicators in LCA (ref. chapter 2) and overall methodology for development of Global Resource Indicator (GRI) is illustrated in Figure 4-1.

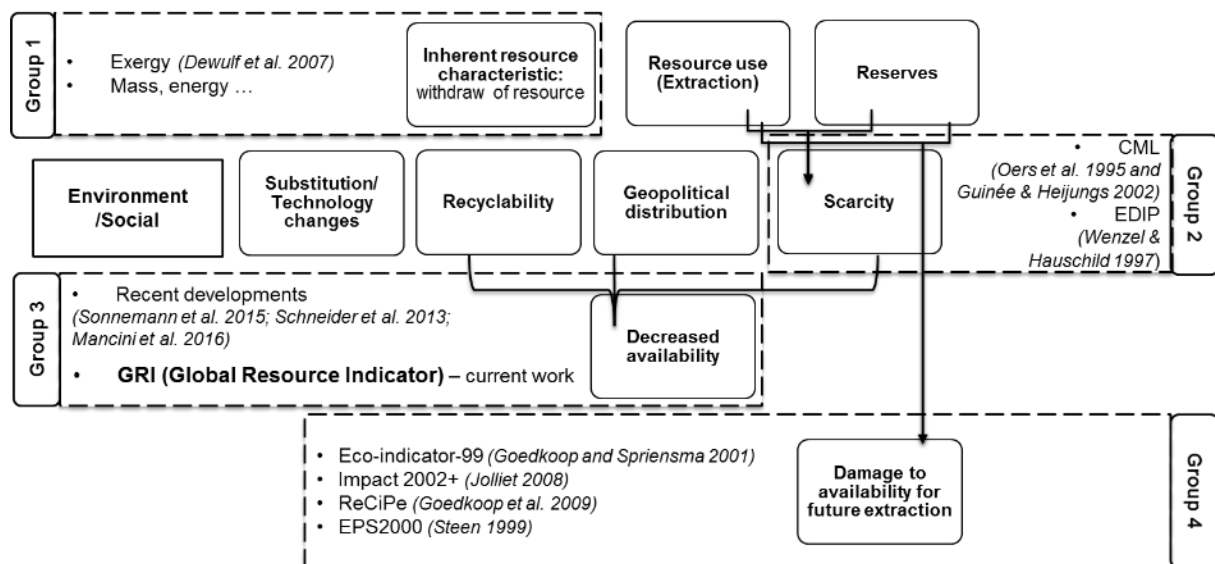


Figure 4-1 Resource assessment cause and effect chain, including groups of indicators in LCA, and overall methodology for development of Global Resource Indicator (GRI) current work.

The chapter also aims at adjusting the aspects and parameters when they are not in line with the proposed core resource consumption and production concept (e.g. adjust methods to cover renewables and non-renewable resources). Also it seeks simple and updatable input parameters so the largest number of Characterization Factors may be produced in the future.

4.2 Methods

Newly proposed Global Resource Indicator (GRI) integrates different resource assessment aspects to improve the characterization of the resources. Different aspects, related to the availability including both recyclability and geopolitical availability of resources are part of the multi-criteria indicator complementing scarcity, Figure 4-2. Including recyclability and criticality enables to go beyond the resource depletion potential (geological availability). The GRI has positive correlation with the scarcity and negative correlation with both geological availability and recyclability.

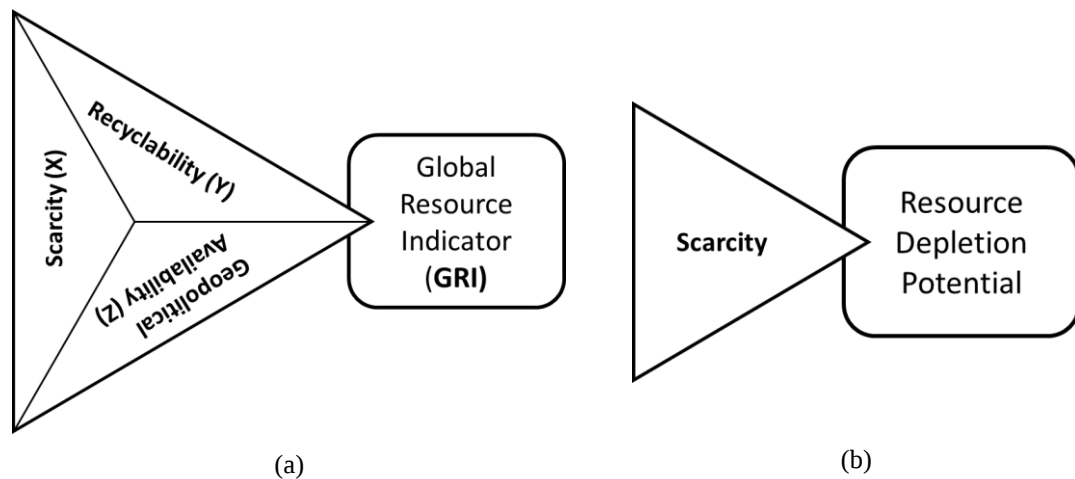


Figure 4-2 Diagram of different aspects of Global Resource Indicator (GRI) (a), compared to the second group, i.e. scarcity resource indicators in LCA (b).

The Scarcity is the first parameter to reflect the available resources in the earth crust. In this work, this factor is derived from CML characterization factors (F_{CML}) in LCA. They are used in group 2 of LCIA indicators.

One of the major new considerations in the proposed GRI is the “recyclability”. Although none of existing LCIA methods consider recyclability and recycling, these parameters influence resources availability. Recycling the resources decreases the depletion of virgin resources, so providing new sources to supply raw materials. The regeneration of renewable resources plays a similar role.

Geopolitical availability is another major point. The Geopolitical availability is defined as the inverse of the criticality for a given resource. The homogeneity of distribution of natural reserves is a resource criticality criteria. If a given resource is accessible in 10 countries, and is distributed evenly, long-term availability of the resource could be guaranteed. The worst case is a situation that a resource is available only in a few countries, especially with high relative concentration within one or two countries. In this case, even if the overall amount of the resource within the crust is considerable, the long-term availability is not assured. From the short-term viewpoint, the geopolitical stability of the territories where the resource is available becomes important.

Criticality and therefore geopolitical availability is not a major issue for recycling related to the anthropogenic stock as the resources are assumed to be recycled where they are used. The recycling happens most of the time near the materials consumption. The virgin resources in the China will become available in Europe by exporting the products, containing raw or processed minerals. Therefore, the more progressed the recycling, the more accessible the materials.

4.2.1 Global Resource Indicator (GRI)

The GRI has positive correlation with the scarcity and negative correlation with both geopolitical availability (inverse of the criticality) and recyclability (Relation 4-1). The formula to calculate the GRI CFs of resources is:

Relation 4-1

$$GRI = \frac{X}{Y \times Z}$$

$$GRI_{Fe-eq} = \frac{F_{CML}^{normalized}}{(1 - F_{dispersion}) \times 10 \times F_{recycling} \times \sqrt[3]{F_{WGI} \times F_{deviation} \times F_{countries}}}$$

$$\times \frac{F_{recycling}^{Fe} \times (1 - F_{dispersion}^{Fe}) \times 10 \times \sqrt[3]{F_{WGI}^{Fe} \times F_{deviation}^{Fe} \times F_{countries}^{Fe}}}{1}$$

In which;

- X, Scarcity, is based on CML characterization factors (F_{CML}) adapted in case of renewable resources.
- Y is Recyclability or quality factor that depends on the dispersion and recycling rates ($F_{dispersion}$ and $F_{recycling}$).
- Z is geopolitical availability. It depends on WGI index, number of countries and standard deviation (F_{WGI} , $F_{countries}$ and $F_{deviation}$).

Nine resources are studied here, some of them are very critical and are used in diverse sectors, including Rare Earth Elements (REEs) [64]: cobalt - platinum - iron - aluminum - copper - silver - wood - sand and gravels - REEs (dysprosium - europium - neodymium).

4.2.2 Scarcity “X” adapted from CML

CML method is an LCIA method, developed by the Institute of Environmental Sciences (CML) of Leiden University [77], [78]. This method covers several impact categories, including resource depletion. CML resource depletion indicator is recommended by International Reference Life Cycle Data System (ILCD) [68], and is also used in Product Environmental Footprint (PEF) method [13] to assess the resources depletion potential. In CML method, dimensionless Abiotic Depletion Potential (ADP) (Relation 4-2) is the annual extraction rates of a given element, divided by the squared reserve of the same element. Iron is considered as the reference substance; therefore, the formula is normalized by Fe. Fe is selected as reliable input parameters are accessible for Iron and the fact that it is more comprehensible compared to Sb for applicants. So, the

CFs of each resource are proportional to Iron. The ADP is expressed in kg Fe-eq (Iron Equivalent).

$$ADP_i = \frac{Ext_i}{Res_i^2} \times \frac{Res_{Fe_i}^2}{Ext_{Fe_i}} \quad \text{Relation 4-2}$$

In which;

- ADP is expressed in kg Fe-eq (Iron Equivalent).
- *Ext* and *Res* in unit of mass.

4.2.2.1 REEs CML Characterization Factors

The Scarcity indicators are derived from the CML 2002 CFs. The CFs of REEs used in this chapter are developed by (Adibi et al 2016) [65]. The CML resource depletion indicator is chosen to reflect the depletion from the point of view of geological reserves.

4.2.2.2 CML Characterization Factors adaptation for renewable resources

For the renewable resources the CML is adapted including the regeneration rate. Regeneration is associated with the duration of renovation of a resource; i.e. the rates of current annual replenishment of species. These factors are especially taken into account for biotic resources. Although the limitations of ecosystems and their renewability may impact human needs and life more than accessibility, this issue needs to be addressed within other LCA impact categories dealing with ecosystem; e.g. land use.

Principally, if the assumption is to assess the availability of a resource, the role of regeneration is very similar to recycling. In order to adapt CML with corresponding regeneration rate, the relation 4-3 is proposed. The regeneration rate is applied to adjust the reproduction as renewable (renewable share of the resource). As an example the regeneration rate is not applied to the forest surface losses for agriculture but to the plantations. For biotic resources, regeneration time ranges from one to several hundred

years. Regeneration rate is obtained based on regeneration time as provided in Relation 4-4.

$$ADP_{i(renewable)} = \frac{Extraction\ as\ loses_i}{(Res_i + (Reproduction\ as\ renewable_i \times Regeneration\ rate))^2} \times \frac{Res_Fe_i^2}{Ext_Fe_i} \quad \text{Relation 4-3}$$

$$Regeneration\ rate = \frac{1}{Required\ time\ to\ be\ regenerated} \quad \text{Relation 4-4}$$

In which;

- ADP is expressed in kg Fe-eq (Iron Equivalent).
- *Ext* and *Res* are expressed in unit of mass.
- *Regeneration rate* is expressed in (1/year).

Example of wood resources: In average wood requires about 100 years to be regenerated in the forest, so the regeneration rate is 0.01 ($= \frac{1}{100}$).

Metals, including nuclear fuel as stock resources, are non-renewable resources (regeneration time is infinite, except for the astronomical processes). For flow resources such as wind and solar power, renewability is instantaneous. For the fossil fuels, the regeneration requires large geological timescales, so they are considered nonrenewable in LCA studies.

4.2.2.3 Sand and gravel CML Characterization Factor

With regard to Sand and gravel, resources of the world are plentiful. However, because of environmental restrictions, geographic distribution, and quality requirements for some uses, sand and gravel extraction is not authorized in many locations. CF of Sand and gravel in this study is taken from the French norm XP P01-064/CN [127] supposing that CF of gravel is equal to Silicium. The authors suggest more assessment in case of Sand and gravel in the future.

4.2.3 Recyclability “Y”

The first part of the indicator is calculating the recyclability (reproduction for renewable resources), variable Y. In the formula, the recyclability is between 0 and 100%. It is multiplied by 1-dispersion rate. Then the result is multiplied by ten to provide a value within the range of one to ten.

$$\text{Let } Y = [\text{Recycling rate} \times (1 - \text{Dispersion rate}) \times 10] \quad \text{Relation 4-5}$$

In which;

- Y is dimensionless.
- *Recycling* and *Dispersion* rate are expressed in %.

Recyclability (Y) shows the availability of the used resource. In another word, none-dispersed part of used material when it is recycled or regenerated. As an extreme case, metals recycling may reach 100%, i.e. ideal recycling without any loss of quality and dissipation in the far future. Metals can be reused many times without losing their functionality, but cannot be regenerated in the ore deposits. In the reality, the ideal recyclability might not be reached due to losses during extraction, transformation, transportation, etc.

4.2.3.1 Recycling rate

The recycling rate is the percentage of an element in discard that is recycled [73]. The end-of-life functional recycling rates (EoL-RR) from UNEP [73] could be used to substitute European recycling data in a global resource prospective. The recycling rate for some of these resources differs from a sector to the other, e.g. in the building sector, these values are quite higher. REEs have small recycling rates because they are used in small quantities, and much dispersed within the products. Quality degradation during recycling is not part of this indicator, therefore future improvement to cover this aspect is recommended.

4.2.3.2 Dispersion rate

Dissipative losses are defined as the losses of materials into the environment, into other material flows, or when reaching permanent waste. The dissipation makes the materials recovery unfeasible technically or economically [128]. Dispersion may happen due to three major issues:

- 1- Intimate mixes between materials inside products: One major reason is that several resources are used in very limited quantities with structural changes in the products.
- 2- Dissipative application: When small quantities of resources are used inside products.
- 3- Technology related dissipation: When the state of material change to non-recoverable state, e.g. to gas or liquid state, e.g. use of metals in paint.

Cobalt has a dissipation rate of 30%-40% [128]. REEs have higher dissipation rates (over 90%), depending on the use of particular REEs. For Platinum group metals, dissipative losses of Pt and Pd from catalysts is between 25% and 30% [128]. An estimation of 20% of silver from extracted ore is returned to the lithosphere as tailings [129]. Copper can be recovered at the rate of 82% from the slag of 3.7% of Cu. So its dissipation rate can be assumed as 18%. Iron and steel industry have mineral processing technology to recover 90% of Fe in steel scrap, so the dissipation is considered about 10% [130]. Considering the high share of recycling in Fe and Al, dispersion rate of aluminum is considered to be 10%. It is mostly because aluminum is used purely and in big quantities in the products, hence easy to recover.

Wood, sand and gravels are considered ignoring the dispersion rate (given their very low dissipation), so the values are not used in the calculations. While Wood, sand and gravels has a low recycling rate. The estimated dispersion rates of resources, in this study are summarized in Table 4-1.

Table 4-1 Dispersion rate of the studied resources [128] [129] [130].

Materials	Dispersion rate
Iron	10%
Aluminum	10%
Cobalt	35%
Platinum	30%
Silver	20%
Copper	18%
Rare Earth Elements	90%

4.2.4 Geopolitical availability “Z” of extractable resources

Geopolitical availability parameters (defined as the inverse of the criticality), related to the extractable resources, are based on three aspects:

- Geopolitical Stability of the countries, where resources are available:

Resource supply has less fluctuations when the resources are in the stable countries. As an example, the cobalt deposits are located in the countries where there are major governmental problems. In many cases the problem is not originated only from the politics but the social, cultural, environmental or security instability.

- Number of countries where a given resource is available:

Even in a well-distributed situation (e.g. two countries with 50% of availability for each, i.e. completely heterogeneous) the resource issue is not yet solved completely, as the two stable countries, might become unstable one day. So, the last input in the method is the number of countries where the resource is available.

- Homogeneity of distribution of a given resource in different countries:

When a resource is expanded over several countries but the major supplier is located in a single country (even if the country is geopolitically stable), we might at any time face supply issues. The geopolitical issue is much less probable when the resource is distributed more homogeneously in different countries.

4.2.4.1 Geopolitical stability

To develop **Geopolitical stability** factors, the World Governance Indicators (WGI) [131] are used, which benefits of a research database in the background, summarizing the views of the quality and stability of countries governance, provided by large number of stakeholders including: enterprises, citizens and expert survey respondents within industrial and developing countries. The WGI project aggregates individual governance indicators from 215 economies over the period 1996–2013, for six dimensions of governance:

- Voice and accountability (V)
- Political stability and the absence of violence (P)
- Government influence (G)
- Regulatory quality (RQ)
- Rule of law (RL)
- Control of corruption (C)

For the aim of this project, we took the estimation of each governance performance that ranges between -2.5 (the weakest) and +2.5 (the strongest) in 2013. As example the governance performance of China in 2013 is composed of Voice and accountability (-1.58), Political stability and absence of violence (-0.55), Government effectiveness (-0.03), Regulatory quality (-0.31), Rule of law (-0.46) and Control of corruption (-0.35).

For each resource, we used the USGS 2013 dataset that shows distribution in different countries. The geopolitical stability index is calculated by Relation 4-6. In this relation, geopolitical stability index is calculated by averaging over all the mentioned WGIs. The results are added by 5 after being multiplied by 2 in order to scale the outputs from the interval of [-2.5, +2.5] to the new interval of [0, 10]. The lower (upper) boundary corresponds to the weakest (strongest) case. For iron, as an example, the x factor is calculated for essential producing countries (Table 4-2). Higher the x less critical is the resource.

$$F_{WGI} = \sum_{i=1}^n \left(5 + 2 \times \frac{V+P+G+RQ+RL+C}{6} \right) \times \frac{D_i}{100} \quad \text{Relation 4-6}$$

D_i : percentage of distribution of resources in each country.

i : index of each country.

n : total number of producing countries.

F_{WGI} : geopolitical stability index (dimensionless), which varies between 0 (the worst case) and 10 (the idol case).

Table 4-2 Geopolitical stability index of main iron producing countries, considering iron (2013) price.

Iron production 2013 USGS	Mt	Di	V	P	G	RQ	RL	C	x_i
USA	31	2,65	1,08	0,61	1,50	1,26	1,54	1,28	0,20
Brazil	26	2,22	0,37	-0,28	-0,08	0,07	-0,12	-0,12	0,11
China	720	61,54	-1,58	-0,55	-0,03	-0,31	-0,46	-0,35	2,41
Germany	27	2,31	1,41	0,93	1,52	1,55	1,62	1,78	0,18
India	50	4,27	0,41	-1,19	-0,19	-0,47	-0,10	-0,56	0,18
Japan	84	7,18	1,10	0,98	1,59	1,10	1,41	1,65	0,55
Korea	39	3,33	0,69	0,24	1,12	0,98	0,94	0,55	0,22
Russia	50	4,27	-1,01	-0,75	-0,36	-0,37	-0,78	-0,99	0,15
Taiwan	14	1,20	0,88	0,86	1,19	1,14	1,04	0,68	0,08
Turkey	9	0,77	-0,26	-1,19	0,37	0,42	0,08	0,11	0,04
Ukraine	29	2,48	-0,33	-0,76	-0,65	-0,64	-0,83	-1,09	0,09
Other	91	7,78	0,00	0,00	0,00	0,00	0,00	0,00	0,39
TOTAL	1170	100							4,59

4.2.4.2 The homogeneity of distribution of a given resource

The homogeneity of distribution is calculated by the ratio of standard deviation (SD) to the height (i.e. 30).

$$F_{deviation} = \left(1 - \frac{SD}{30} \right) \times 10 \quad \text{Relation 4-7}$$

The worst case is $SD > 30\%$. It means that resources are not evenly distributed and there is a high risk of monopoly. The maximum $SD = 30\%$ is then chosen since the highest

obtained SD is 27.92%, corresponding to platinum. Values of "y" vary between 0 (the idol case) and 10 (the worst case: SD=30%).

$$\text{For iron: } F_{deviation} = (1 - \frac{17.715}{30}) \times 10 = 4.094$$

4.2.4.3 Number of countries where a resource is available

This parameter, $F_{countries}$, is calculated by the ratio of the number of countries where a resource is available to the highest number among all resources, i.e. 20 (Relation 4-8).

$$F_{countries} = \begin{cases} \frac{n}{20} \times 10 = \frac{n}{2}; & 0 < n < 20 \\ 1; & 20 \leq n \end{cases} \quad \text{Relation 4-8}$$

The main assumption here is that when a resource is extractable in more than 20 countries, there is no risk of monopoly, excluding other countries as defined here. In calculating "z", all the countries with the production rate contributing together to less than 10% of the world total production (USGS tables of production) are grouped into "other countries". The "z" value is again between 0 (the worst case) and 10 (the best case).

$$\text{For Iron: } n = 11 + 1 = 12 \text{ so } F_{countries} = 6.$$

4.2.4.4 Geopolitical Availability (GA)

Three averaging operators are used for combining these three geopolitical factors, x, y and z, and to calculate the geopolitical availability.

$$1\text{- Simple Arithmetic Averaging} = \frac{F_{WGI} + F_{deviation} + F_{countries}}{3}$$

$$2\text{-Weighted Arithmetic Averaging} = 0.5 F_{WGI} + 0.25 (F_{deviation} + F_{countries})$$

$$3\text{- Geometric Averaging} = \sqrt[3]{F_{WGI} \cdot F_{deviation} \cdot F_{countries}}$$

The distribution percentage of the REEs are taken from the tables, provided by Adibi et al (2016) [65]. The results of these three averaging strategies for different resources are presented in the Table 4-3.

Table 4-3 Calculation of the geopolitical availability, using the three integral operators.

	1- simple arithmetic	2- weighted arithmetic	3- geometric
iron	4,82	4,90	4,96
aluminum	6,63	6,22	6,47
copper	6,92	6,64	6,87
sand and gravel	8,04	7,72	7,93
platinum	3,11	3,62	2,32
cobalt	4,90	4,58	4,81
silver	6,19	5,92	6,07
wood	8,42	8,02	8,32
Dy	5,15	5,82	4,79
Eu	5,53	5,48	5,45
Nd	5,27	5,27	5,23
La	5,04	5,03	5,02
Ce	4,90	4,89	4,89
Pr	5,16	5,15	5,13
Sm	5,71	5,80	5,64
Gd	5,58	5,90	5,50
Tb	5,19	5,60	5,06
Ho	4,07	5,01	3,32
Er	4,47	5,35	3,88
Tm	3,83	4,89	2,64
Yb	4,77	5,41	4,48
Lu	4,75	5,34	4,50
Y	5,10	5,85	4,62

The third integration operator seems to be the best, since the geometric averaging is more sensitive to the extreme values. For example: imagine a resource with $F_{WGI}=1$, $F_{deviation} = 9$ and $F_{countries}=9$, this resource is well distributed (due to y and z) but the producing countries have serious political problems ($F_{WGI}=1$) and the situation is not stable at all.

- 1st operator $\rightarrow$ GA= 6.33
- 2nd operator $\rightarrow$ GA= 5
- 3rd operator $\rightarrow$ GA= 4.32

4.2.5 Sensitivity analysis on the GRI parameters

Any change in the indicators of GRI (relation 4-1) influences the results significantly. We made a sensitivity analysis on the indicators and provided a graphical illustration of changes in the GRI CFs. Figure 4-3 shows sensitivity of the CFs to each sub-indicator. The sensitivity curve is exponential for all the factors. Only dispersion rate has a positive correlation with the impact. Dispersion rates vary from 10 to 90 % for the studied resources. The geopolitical availability indicators vary from 2.32 (lowest) to 8.32 (highest). Recycling varies for short term indicator from 1 to 68 %, while long term recycling given the technology improvements is assumed to be 90%.

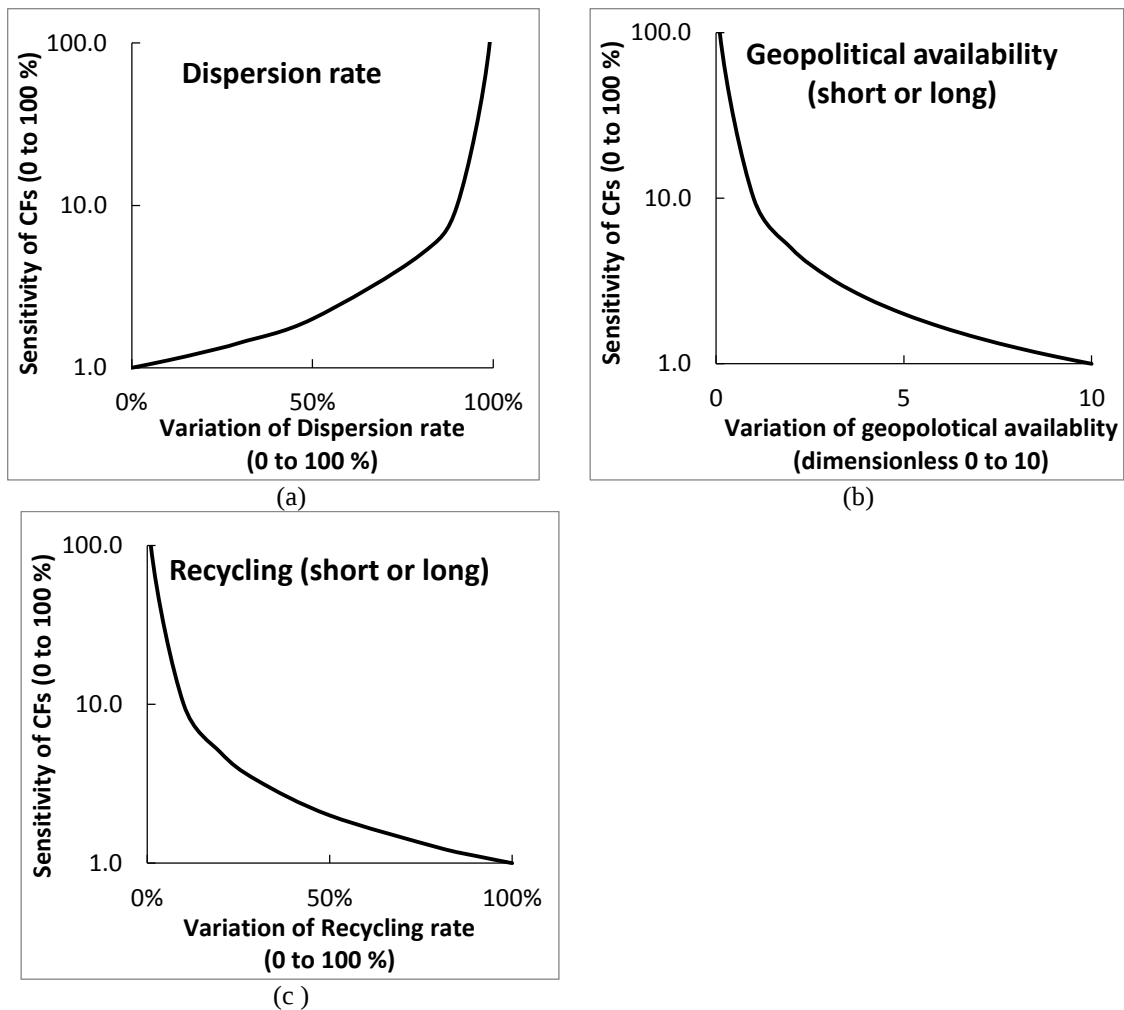


Figure 4-3 Sensitivity of the CFs with regard to subcategories. a) Dispersion rate b) Geopolitical availability (short or long) c) Recycling (short and long)

4.3 Results and Discussion

The CFs of $\frac{X}{Y.Z}$ accounts all the indicators (extraction rate, recyclability, regeneration rate, dispersion rate, etc.). In CFs, all the indicators (X, Y and Z) are considered with the equal importance. Z and X are respectively geopolitical availability and CFs of CML, normalized by Fe. Y and Z have different tendencies, compared to X. Higher values of Y and Z, and lower values of X show more availability of the resource. That is why Y and Z were introduced in the denominator. The obtained results are shown in the Figure 4-4 to reveal how the CF varies, using different indicators.

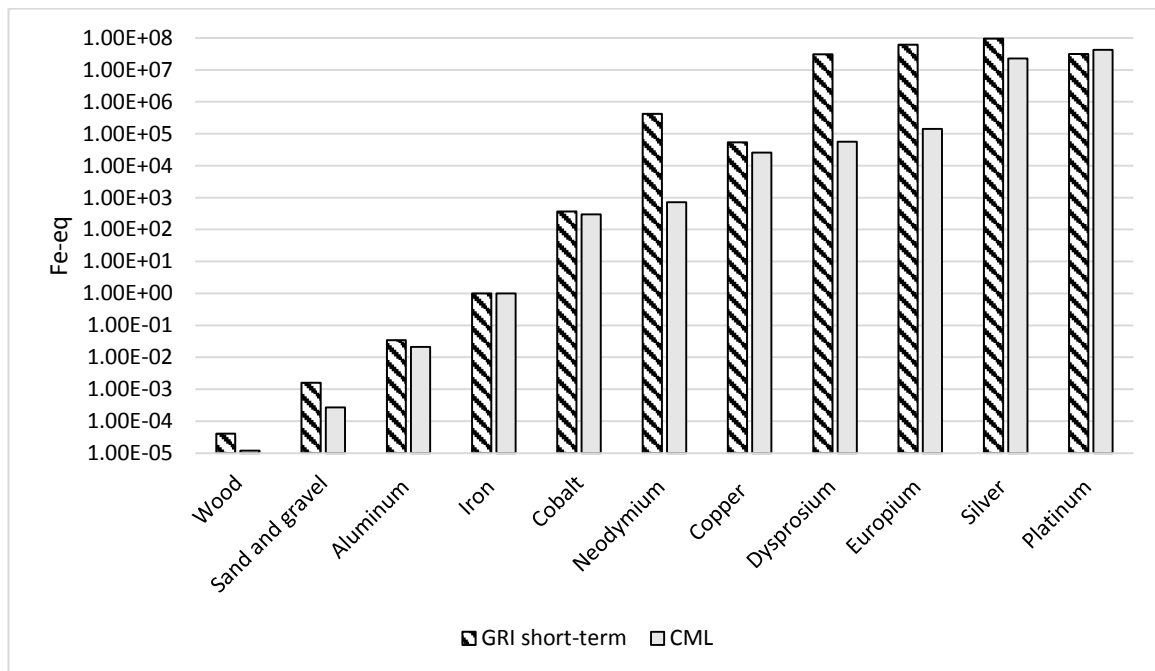


Figure 4-4 CFs variation in GRI compared to CML.

Comparing the results with CML factors, all resources show higher impacts (CF increases for short-term). Comparing to CML, it is found that most of resources are highly influenced by introduction of the other indicators.

Due to very uneven distribution of REEs in the counties, also the instability of the corresponding counties, the factors of REEs are changed the most. This variation could

be understood, comparing factors with the CML CFs. Actually, REEs have a recycling rate of 1 % in Europe, which is very low.

4.3.1 Short versus Long term vision

The LCA-based approaches in assessing environmental impacts are based on long-term prospective (more than 50 to 100 years). Short-term concerns are mostly related to the resources that are under the risk of geopolitical constraints, geostrategic considerations, social concerns or environmental legislations. The main environmental consequence of the short-term concerns is the supply risk of the resources, used in sustainable products. As an example, shortage in the rare earth supply, affects the development and the use of green technologies (wind turbines, photovoltaic panels, etc.). Nevertheless, interpretation of these indicators needs to be done jointly with long-term resource indicators to provide valid results. Today, these two visions are most of the time making overlaps and even mixed in most recent developments. It is crucial to differentiate the short- and long- term issues in LCA.

In this indicator both short term and long term CFs are distinguished. Two indicators affect the short and long term changes:

4.3.1.1 Recycling rate

Recyclability values are assessed in this study, based on the recycling rates in Europe, and are used to obtain short-term indicators. For long-term indicators, it is assumed that recyclability is expected to reach 90% due to technological development of recycling in the far future except for wood where 50% wood for energy is considered.

4.3.1.2 Geopolitical availability

The geopolitical stability is not applied to the long-term Geopolitical availability, since the geopolitical stability is considered as a short term indicator. In this case, Geopolitical availability, Z , is calculated following relation 4-9.

$$GA_{short-term} = \sqrt{F_{deviation} \times F_{countries}}$$

Relation 4-9

Where, $F_{deviation}$ is the homogeneity of distribution of a given resource, and $F_{countries}$ is the abundance of countries where a given resource is available. Considering both long term recycling rate and geopolitical availability (GA), the Table 4-4 provides the CFs for both short-term and long-term assessment of each resource.

Table 4-4 calculation of Characterization Factors for short- and long-term resource assessments.

**All values, from the CML are converted to Fe-eq. *Wood is renewable, CF is obtained based on adapted renewable CML.

Resource	Y	Y	Z	Z	X adapted CML CFs (Fe-eq **)	CFs	
	short-term	long-term	short-term	long-term		short-term	long-term
Iron	1.000	1.000	1.00	1.00	1.00E+00	1.00E+00	1.00E+00
Aluminum	0.790	1.000	1.30	1.43	2.09E-02	3.44E-02	2.99E-02
Copper	0.676	0.911	1.39	1.45	2.60E+04	5.35E+04	4.14E+04
Platinum	0.627	0.778	0.47	0.30	4.23E+07	3.17E+07	1.63E+07
Cobalt	0.792	0.722	0.97	1.07	2.99E+02	3.66E+02	4.43E+02
Silver	0.287	0.889	1.22	1.28	2.26E+07	9.61E+07	3.25E+07
Dysprosium	0.002	0.111	0.97	0.73	5.68E+04	2.75E+07	3.74E+05
Europium	0.002	0.111	0.78	1.07	1.41E+05	5.50E+07	1.36E+06
Neodymium	0.002	0.111	1.05	1.01	7.21E+02	3.79E+05	6.56E+03
Wood	0.358	0.617	1.68	1.78	8.68E-06*	4.07E-05	2.50E-05
Sand/gravel	0.269	1.111	1.60	1.66	2.67E-04	1.59E-03	3.99E-04

In case of long-term, it is assumed that the recycling of the resources reaches 90%, therefore their impact is reduce significantly compared to the short-term factors except cobalt where the geopolitical availability is increased when the geopolitical stability is not considered. The factors of REEs are changed the most comparing short and long term factors. This variation is due to the high geopolitical instability of the countries at short term. Additionally, the actual REEs recycling rate is 1 % in Europe. However, we assumed that in the future, the recycling rate will reach 90%, so the factors are improved.

4.3.2 Technology changes and substitution

If we assume that technology changes improve the resource assessment parameters: dispersion rate, recycling rate, quality degradation, etc. then the GRI needs to consider these improvements through the time. Substitution is another major issue. The technology has played an important role in finding substitutions for various elements or materials. As an example, the supply shortage due to geopolitical concerns, e.g. on REEs, was partially solved by industrial development through finding some extend substitutions e.g. substitution of REEs by other metals and technologies in car industry. Another famous example is banned elements due to safety problems, e.g. the asbestos and many other materials were phased out of buildings. For sure, the substitution and technology adaptations are most of the time unpredictable, occasional, complex and resulted from focused research investments. The substitution is not part of in this work. The authors suggest further research regarding the substitution and its effects in the future. A first attempt in this direction for building and construction sector was done and is provided in Appendix 5.

4.4 Application of CFs in the wind turbines and assessment of the results

Several LCA studies investigated the environmental impacts of wind turbines. Studies focus on assessment of impacts [132] and highlight the potential improvements [133]. In some cases comparisons are made between available technologies and their performance in different geographical zones [134]. This section describes results of resource evaluation based on GRI indicators. They highlight the influence of the new indicator on resource assessment of wind turbines.

Datasets of two different types of 3MW wind turbine were obtained from Crawford et al. [135], and complemented using the permanent magnet LCI. The wind turbine towers can be made of iron, concrete or hybrid. For each type, either wind turbines contain REEs (DDPMG) or not (DFIG) generator. Different wind turbines scenarios are provided in

Table 4-5 table 5 and their respective composition is provided in table 6. The main components of the wind turbines include the rotor (hub and blades), nacelle (generator, gearbox, brakes, electronic controller, transformer, and control system), tower and base. The four wind turbines chosen for this study were horizontal axis, 3 blade systems derived from Crawford, 2009.

Datasets of four different types of 2.5 MW wind turbine were extracted from SimaPro Software. The wind turbine can be made of iron, concrete or hybrid. For each type, either wind turbines contain REEs (DDPMG) or not (DFIG) generator. Different wind turbines scenarios are provided in and their respective composition is provided in Table 4-6.

Table 4-5 Scenarios of different wind turbines studied.

Scenario 1: DFIG Iron	Double Fed Induction Generator, towers made of Iron
Scenario 2: DDPMG Iron	Direct-Drive Permanent Magnet Generator, towers made of Iron
Scenario 3: DFIG Concrete	Double Fed Induction Generator, towers made of Concrete
Scenario 4: DDPMG Concrete	Direct-Drive Permanent Magnet Generator, towers made of Concrete

Table 4-6 Composition of different types of wind turbines Crawford et al. [135]. *The copper is used as winding wires (recyclable).

Material		Part	DFIG Concrete	DDPMG Concrete	DFIG Iron	DDPMG Iron
Steel	kg	Rotor	730	730	730	730
Iron Cast	kg	Rotor	19200	19200	19200	19200
Glass fibers (~sand)	kg	Rotor	12040	12040	12040	12040
Epoxy resin	kg	Rotor	8030	8030	8030	8030
Steel	kg	Tower	77122	158760	158760	158760
Paint	kg	Tower		1240	1240	1240
Concrete	kg	Tower	590000			
Steel	kg	Fondation	36000	36000	36000	36000
Concrete	kg	Fondation	1140000	1140000	1140000	1140000
Copper	kg	Nacelle	2561	2561	2561	2561
Aluminum	kg	Nacelle	2311	2311	2311	2311
Steel	kg	Nacelle	55290	55290	55290	55290
Plastics	kg	Nacelle	700	700	700	700
Copper	kg	Generator	1430	14	1430	14
Steel	kg	Generator	5710	1268	5710	1268
Neodymium	kg	Generator		415		415
Dysprosium	kg	Generator		4		4

These quantities are multiplied by the proposed characterization factors, and results are obtained and presented in Table 4-7.

Table 4-7 Application of CFs on different wind turbine types.

Wind turbine (Different types)	CML-Fe eq	GRI kg-Fe eq short-term	GRI kg-Fe eq long-term
DFIG Concrete	1.04E+08	2.14E+08	1.65E+08
DDPMG Concrete	6.77E+07	4.05E+08	1.11E+08
DFIG Iron	1.04E+08	2.14E+08	1.66E+08
DDPMG Iron	6.77E+07	4.05E+08	1.11E+08

The Figure 4-5 illustrates the results for the four wind turbines technologies. The impact is attributed less than 40% to copper and more than 60% to Dysprosium and Neodymium. Dysprosium with a 4 kg mass (0.00021 %) represents 25% of total impacts. Although a significant mass of copper (around 4 t) is used in the product, applying the new indicator highlight the importance of the rare earth elements in DDPMG (both iron and concrete). The use of REEs in these application is identified as hotspot applying the indicator.

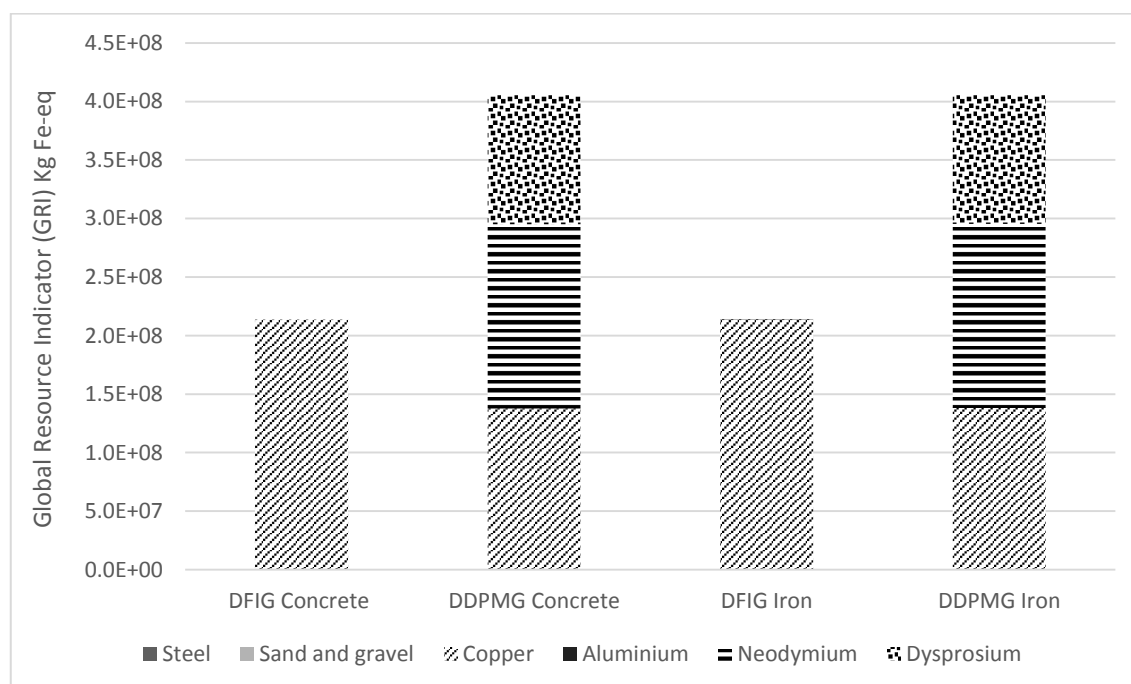


Figure 4-5 GRI results for the 4 wind turbines technologies at short term.

Due to the Figure 4-6, wind turbines with REEs (DDPMG) have the highest impact at short-term. The problem with these elements is that they are very dispersed within the products, so recyclability rate is about 1%. Technological enhancement for increasing recyclability of REEs may help the security of the resources. The CML impacts are almost 100% resulting from the copper. The limit of this case study is a very dominant quantity of copper. The strength of the indicator may be better highlighted in case of application in a product with a more homogenous diverse composition of materials.

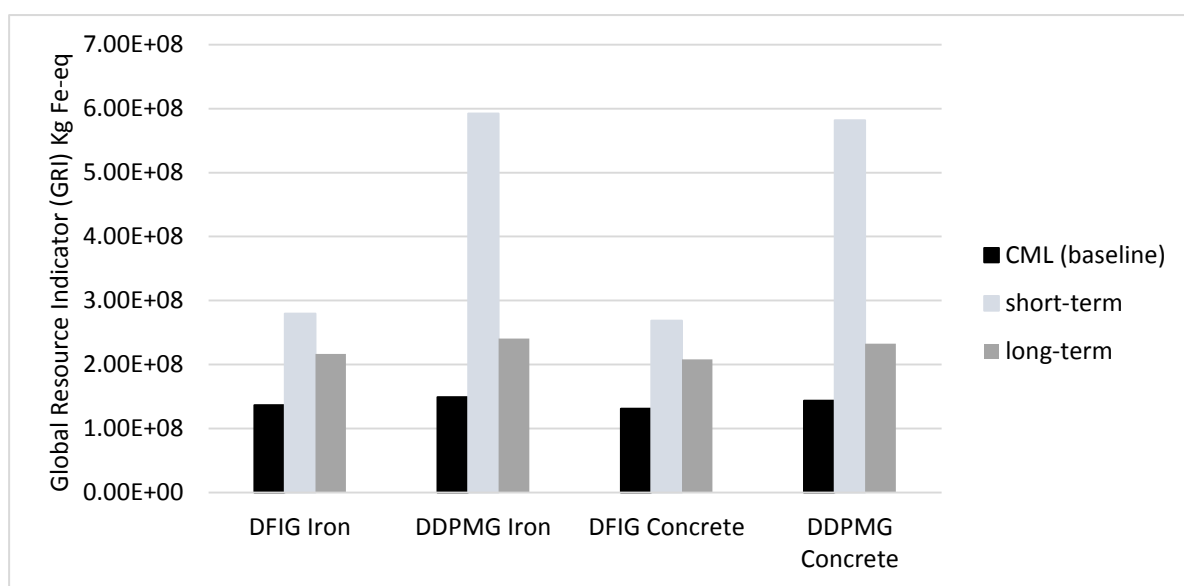


Figure 4-6 Comparison between four different types of wind turbines (i) CML baseline (ii) short term GRI and (iii) long term GRI in Fe-eq.

4.5 Conclusion

Resource assessment and circular economy are defined as topics of growing interest at business, governmental and research contexts. In this work we propose a new multi-criteria indicator to develop, new characterization factors taking into account different criteria, affecting resources life cycles. In place of a simple depletion potential, Global Resource Indicator is proposed. Both recyclability and Geopolitical availability of resources are part of the method complementing scarcity.

Most of resources are influenced by introduction of the additional indicators. The results also showed that the order of importance of resources are influenced when additional indicators, including recycling is taken into consideration. This is also the case comparing the results with CML characterization factor. The results also show that if short and long term aspects are tackled correctly, they influence significantly the resource classification.

The Global Resource Indicator, may cover all types of resources (renewables and non-renewables). Data needed to develop the missing additional characterization factors are relatively simple to provide. Therefore gaps may be filled compared to existing LCA resource assessment indicators.

Finally the CFs derived from the new method are tested in a case wind turbine and the applicability is validated. In addition the below aspects are the point to improve within the next resource related works based on the results and limits of the current work:

- Accessibility is not addressed in this chapter as there is a need to link the accessibility to the extraction, use and anthropogenic, separately.
- Dynamic models seems crucial, the methodology needs to consider a big picture of the material circulation during its life cycles, and the quantities of each stock (extraction, use and anthropogenic) to be predicted over the time.

The substitution is not part of the proposed indicator and needs to be elaborated in the resource assessment.

5. Resource accessibility: a non-monetary value oriented approach for Life Cycle Assessment in Circular Economy context

Highlights

- Resource assessment differences from viewpoints of circular economy and LCA are discussed.
- Anthropogenic-based predictor algorithm is proposed and applied.
- Accessibility is calculated in a stable consumption.
- New sets of resource impact assessment indicators are proposed: applicable based on circular economy versus LCA point of view.

5.1 Introduction

Today consumption and production patterns and the population growth is directing the human being to the problem of resource accessibility¹¹. Even with the improvement of overall recycling system, the demand for resources is set to continually increase due to the population increase, higher urbanization rates and consumption amplification [136], [137]. Therefore, more adapted economic and business models are needed to turn a transition to a more circular economy where our finite natural resources are managed more efficiently [138], i.e. linking extraction and recycling. Different global, European, national and regional institutions adopted different drivers [123]–[126] to facilitate this transition [139]. At European level, a newly adopted Circular Economy package [123], [124] aims to make Europe’s economy cleaner and more competitive. The concept has also been adopted by countries like China as the basis of their economic development [140].

The point of departure in defining Circular Economy is the fact that biological ecosystem is not able to sustain the natural resource extraction, energy consumption and the waste generation due to the human activities [141]. The primitive work done by Leontief in 1991 [142] followed by the recent attempts to develop the principal of economic and biological systems as circular flows, led to development of Circular Economy concept [141]. One of the most elaborated definitions of Circular Economy is provided by Murray et al., where it is defined as “an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being” [140].

From the resource prospective, Circular Economy focuses on the design for reuse and remanufacturing [143], therefore “making a closed loop” of product life-cycles through recycling and bringing benefits for both the environment and the economy [144]. In some

¹¹ Accessibility is approachability of resources also refers to the quality of being available when needed.

cases making a closed loop requires more energy. Waste, losses and quality degradation of resources are never equal to zero, therefore additional resources and materials are required to close the loops. All these additional efforts need to be assessed and compared with benefits of the closed-loop resources economy. The benefits of resource economy needs to be assessed in this case and compared with the potential additional impacts, generated in case of closed-loop.

5.1.1 Resources in Life Cycle Impact Assessment

Considering different life cycle stages of a product/service, LCA can be used as a decision making tool to support a transition to a new economic models, including circular economy, as well as provide a systematic environmental assessment approach of a product, a service or a process. Given the definition of the Circular economy (Murray et al.) one may conclude that what is measured by LCA, provides an answer to the overall question of Circular Economy. LCA results may be used to assess a burden, related to Circular Economy approaches of the products, processes and services at micro-level. Publications present application of LCA in the Circular Economy context [145], [146].

The weakness of LCA in this context is: the first debatable resource indicator used in LCA to assess the burdens related to the resource depletion (for detail cf. chapter 2 section 2.5); and secondly and the most important, LCA with its current indicators fails to provide an applicable material-product management decision making resource indicator based on potential Circular Economy benefits of different resources.

In this chapter, we focus to provide resource indicators where the future provision of needs and resource function is considered covering a comprehensive resource circulation in economy considering aspects, e.g. technical and economic availability of resources. The indicators reflect the potential (or importance) of different resources with regard to Circular Economy. It means, does it worth putting efforts (energy, emissions, etc.) in closing the loop? Which resources are the Circular Economy hotspots? Is priority to shift to the alternative resources, or change/adjust the design, or developing the associated recycling sectors? The indicator is a value oriented non-monetary indicator. Similar

indicator was developed by Franklin-Johnson et al. [141] where resource duration was introduced as a Circular Economy indicator. The longevity indicator measuring the material retention based on the amount of time a resource is kept in use. The new indicator proposed in this chapter focuses on the accessibility and inaccessibility of resources while integrating the life time of the resources within different application.

5.1.2 Resource assessment in Circular Economy

Products and materials are two phases of a larger environment: anthropogenic. LCA focuses on the damages caused by human as well as the exchanges between the nature and material phase. In other words, LCA assesses the exchanges from ecosphere to techno-sphere and vice versa. As discussed in Chapter 2, resource LCA impact assessment methods focus mainly on depletion of natural resources.

Circular Economy addresses two main types of flows: nutrients reentering the biosphere and materials moving continuously within industrial systems [147]. In this chapter we focus solely on the material flows in the economy. The Circular Economy aims to close a loop to obtain the maximum share of necessary materials from the recycled part. Four environments, six stocks and seven rates are basic concepts used in this chapter, which are defined and illustrated in Chapter 2 (cf. 2.5) and Figure 2-4.

5.1.3 Resource Accessibility Indicator

In the current chapter, a new two-step methodology, based on the overall resource consumption is introduced.

- Step 1: Anthropogenic-based prediction algorithm (model resource circulation and future prediction)

The quantities of different stocks: use, reserve, virgin material, recyclable, losses (wastes), recycled as defined in Chapter 2 (cf. 2.5) and the transfer from use to recycled (F_{USE}), recycled to use (F_{REC}), reserve to use (F_{RES}) is predicted during the years, up-to 2170. For developing the closed-loop, a recursive calculation is used. Accessibility (from

virgin earth resources, product stock and recyclable stock) is taken into account, which has provided a broader vision toward the problem, compared to previous models, based only on earth resources. The “product stock” plays an important role in our model. It is split into: “virgin product” and “recycled product”, based on its supplying source. Splitting the product stock is important in calculating recycling content.

- Step 2: Accessibility-stable product stock (assess the accessibility)

A few decades after convergence of the population, the consumption will converge. Two main indicators are obtained at the consumption constant level. The first one is applicable at the natural resource extraction level and second one is applicable to recycling (Circular Economy) level. For natural resource extraction the inaccessibility is assessed, which means less approachable resources at extraction level leads to higher inaccessibility impact. Regarding the Circular Economy indicator, more approachable recyclable resources leads to higher impact. This means that the more accessible the recyclable stock is, there is more potential to utilize them as the recycled content in the product (or less recycled content feeds the use phase). Therefore, the final impact of the resource is higher when the accessibility of recycling is higher. The indicators (Inaccessibility reserve / Accessibility Recycling) and their position within impact assessment methods is illustrated in Figure 5-1.

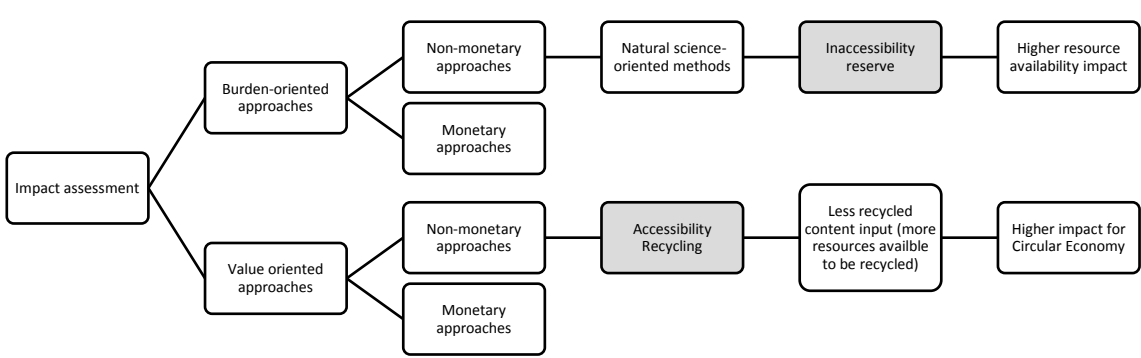


Figure 5-1 Overview of the two indicators (Inaccessibility reserve / Accessibility Recycling) within the impact assessment methods.

Three main indicators are established to define the inaccessibility and accessibility of natural resources and recyclable resources introduced in the content matrix (C): dimension of the Stock here are called Flow to Stock ratio (F/S) (the transferred amount divided by the stock from which the transfer happens), geopolitical availability (GA) [148] and cross coefficients (CC).

The new indicators proposed in this chapter are based on the material circulation during its life cycles. The aim of this chapter is to provide a new consistent approach to empower the use of LCA in a comprehensive resource assessment. The method is also developed to support the decision making through the framework of circular economy. The ultimate goal is to develop an approach to reinforce the link between LCA and circular economy and to provide the resource characterization factors based on the both prospective.

5.2 Methods

5.2.1 The Anthropogenic-based prediction algorithm

5.2.1.1 Population assumption and consumption data

A dynamic time-dependent algorithm is designed at first to predict the material amounts in each stock box. The availability of extraction data defines the starting year of the algorithm, e.g. 1990 for iron deposits. Combination of extraction data and recycling history are considered as historical consumption. The annual consumption for the future is predicted by a linear relation between consumption and population (Figure 5-2). A moderate scenario is considered for consumption prediction (Figure 5-3) [149].

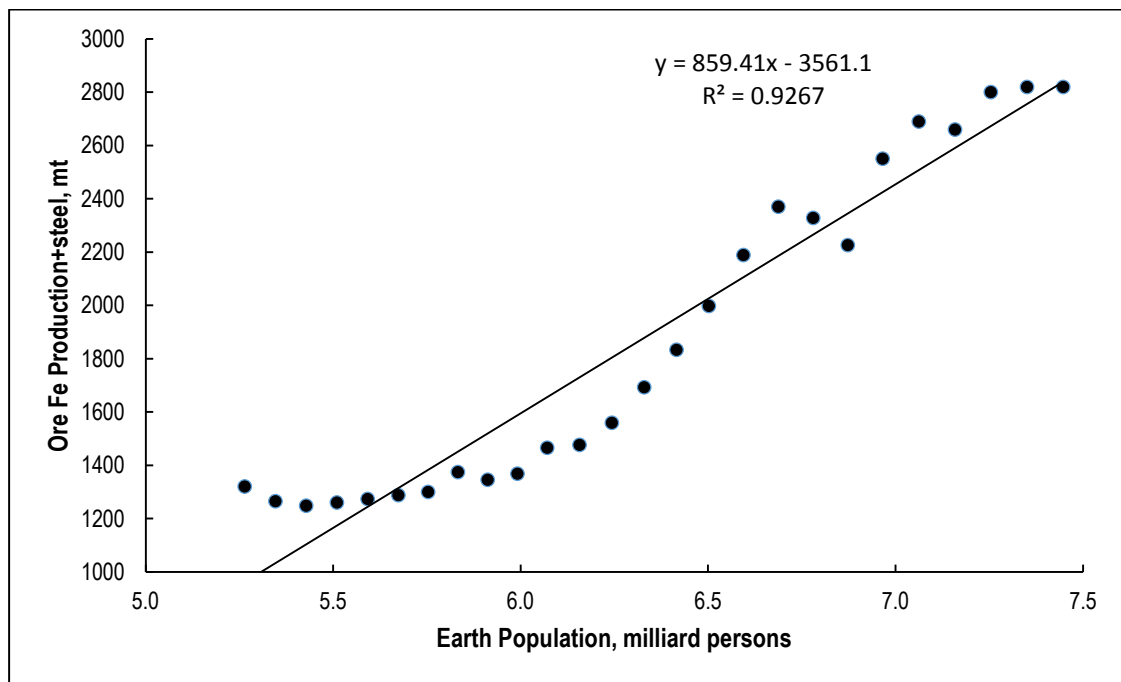


Figure 5-2 Linear regression between iron consumption and the population of the earth (1990-2015) [149].

Based on the moderate UN population scenario, earth world population will reach to its peak in 2075, from then, it gently converges to about 8.4 milliard of inhabitants (Figure 5-3). Due to the convergence of population (after 2150), the assumption of stability of the product stock will be effective.

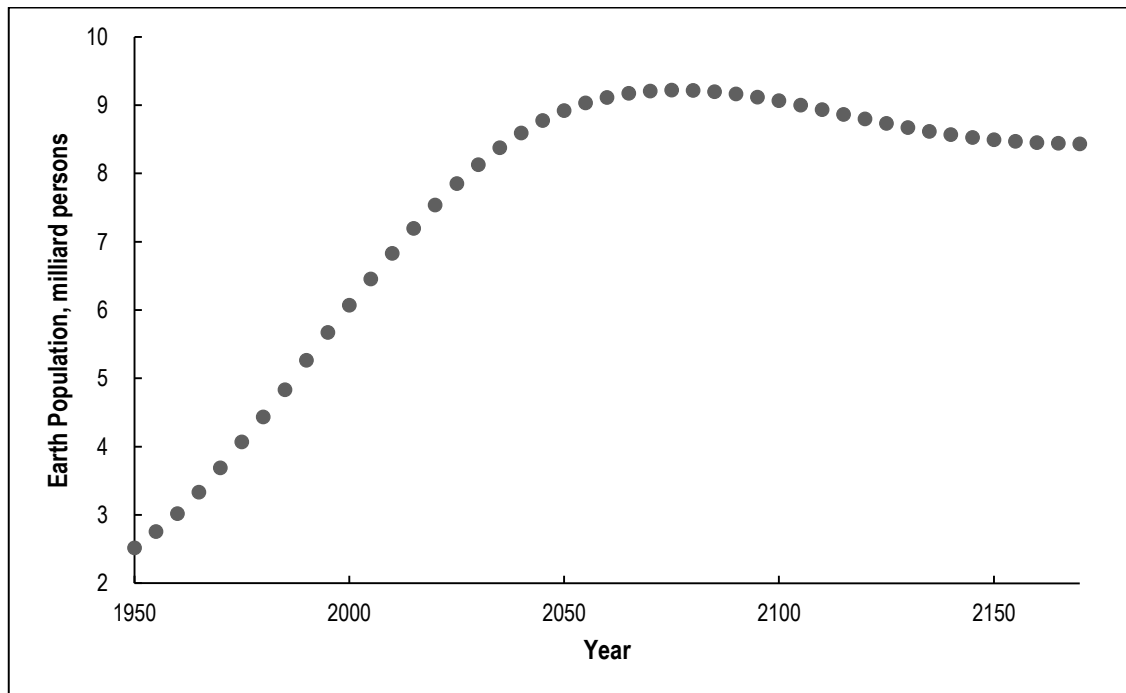


Figure 5-3 Moderate scenario of earth-population between 1950 and 2170 [149].

The extracted amount from the reserve stock constitute products. Products are used in different functions, like building and construction, automobiles, various industries, etc., with different functional life. The average functional life of materials (e.g. 27 years for iron) are inserted into the model as the rest time in the product stock. Once the functional life of the material is finished, the recovery rate controls which portion of used materials should be fed into the recyclable stock, the other portion will be dissipated into the losses stock and the environment. The recycling rate will feed back the material from the recyclable stock to the recycled stock, successively to the product stock.

5.2.1.2 Reserve data

The last input is historical reserve data, extrapolated in the future with the same trend (Figure 5-4). The curve consists of three parts: (i) historical reserve data [99], (ii) a linear extrapolation of the historical part over the years. The extrapolation is done based on the fact that the exploration activities will lead to discover further reserves. Besides, technological progress will give hand in extracting from low-grade resources. (iii) The

third part starts when we reach the reserve base content e.g. from the year 2144 for iron deposits. In this year, the extrapolation model exceeds the earth iron reserve base (230'000 mt), so we have applied the highest reserve base as a cut-off (Figure 5-4). In case reserve base data is not available or if the reserve base data was not enough to support the consumption up-to the stability year (2170), then the available resources were considered.

The reason why sometimes resource values are used in some cases is that: “reserve” is a subcategory of “resource”. Peak production or exhaustion cannot be modeled accurately from reserves. For example, reported copper resources are two times larger than required amount till 2050. Besides, an estimation of unexplored copper resources declares that the geological reserves of the copper is up-to 40-times huger than the well-explored resources, which could supply the required copper for the centuries [150].

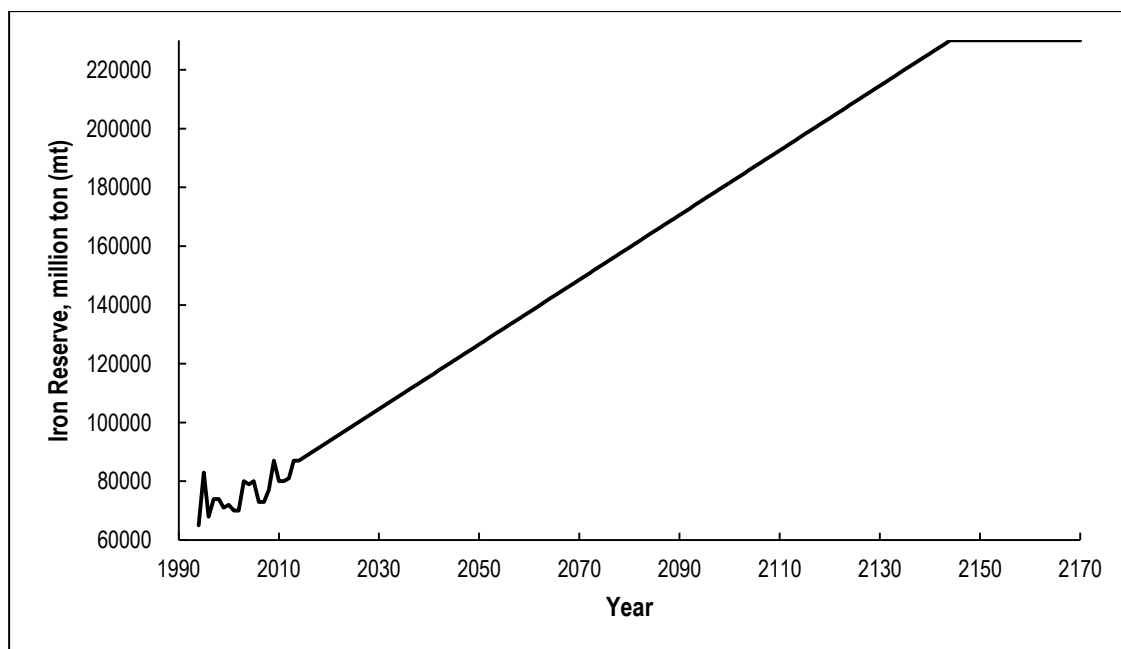


Figure 5-4 Iron reserve assumptions: Part (i): historical data (1994-2015) from[99]. Part (ii): future extrapolated data. Part (iii): considering cut-off of iron earth reserve base, 230'000 mt.

5.2.1.3 Recovery rate, recycling rate, quality degradation and functional lifetime

The recovery rate and functional lifetime of the resources are estimated based on the defined applications of resources (construction, automotive, machinery, electrical and domestic appliances). The UNEP [53], [70]–[73] report consists list of applications for different resources. Crossing the application list with recovery rates and functional lifetime for each application (Table 5-1), both average functional recovery rate and functional lifetime are calculated for each resource (Table 5-2). We suggest further investigation on using the input-output economic table to weight these values based on the importance of resources in each application in different regions.

Table 5-1 Recovery rates and functional lifetime for different applications.

	Actual Recovery rate in 2007 (%)	Estimated recovery rate in 2050 (%)	Average of Life cycle range in years	Life cycle range, in years
Construction	85	90	55	40 – 70
Automotive	85	90	11	7 – 15
Machinery	90	95	15	10 – 20
Electrical and domestic appliances	50	65	7	4 – 10
Weighted global average	83	90	N/A	N/A

Table 5-2 Parameters of the algorithm, regarding recovery of used materials.

Symbol- Element	Main applications	Recovery rate 2007 (%)	Estimated recovery rate 2050 (%)	Average Life cycle, in years
Fe – Iron	The basis constituent of ferrous metals	87	92	27
Al – Aluminum	Construction and transportation	85	90	33
Co – Cobalt	Super-alloys, catalysts, batteries	68	78	9
Cu – Copper	Conducting electricity and heat	78	85	22

Ag – Silver	Electronics, industrial applications (catalysts, batteries, glass/mirrors), jewelry	68	78	9
Pt – Platinum	Auto catalysts	85	90	11
Wood	Construction	85	90	55
Sand and Gravel-	Construction	85	90	55
La – Lanthanum	Batteries	75	83	11
Ce – Cerium	Catalyst	85	90	11
Pr – Praseodymium	– Glass manufacturing and magnets	70	80	11
Nd – Neodymium	Magnets	70	80	11
Eu – Europium	Magnets	70	80	11
Gd – Gadolinium	Magnets	70	80	11
Dy – Dysprosium	Magnets	70	80	11

The recycled content is derived from the UNEP report to update the consumptions, after 2007 by adding the recycled materials [53], [70]–[73]. In order to have precise values for the recycling rate of each resource, we used the values provided at European level, as presented and used in Global Resource Indicator [148], and the steep of the curve of recovery rate is used for predicting recycling rate (Figure 5-5). The recycling rates provided by UNEP are not precise enough, since they express recycling within the range of values [53], [70]–[73]. The quality degradation is assumed to be 2% for all the resources as no reliable report is available at the moment. An example of assumed recovery and recycling rates for iron is presented in Figure 5-5. Further investigation about quality degradation will precise outputs of the current algorithm. Based on the previously introduced concepts, the anthropogenic-based algorithm is designed in four stages (Figure 5-6).

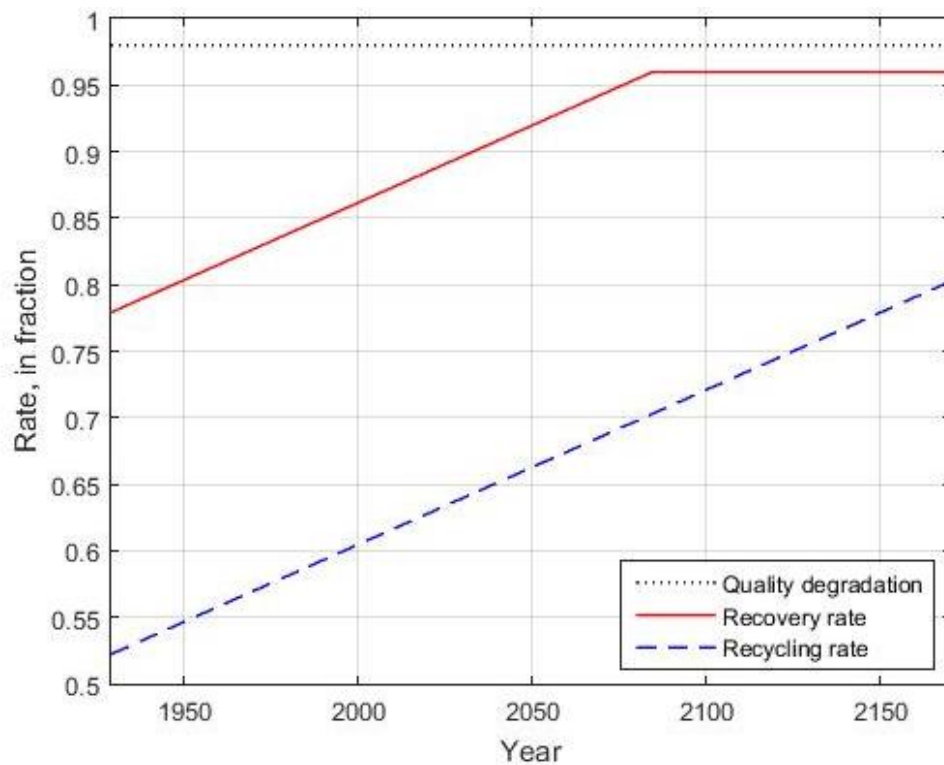


Figure 5-5 The curves of quality degradation, recovery and recycling rates for iron.

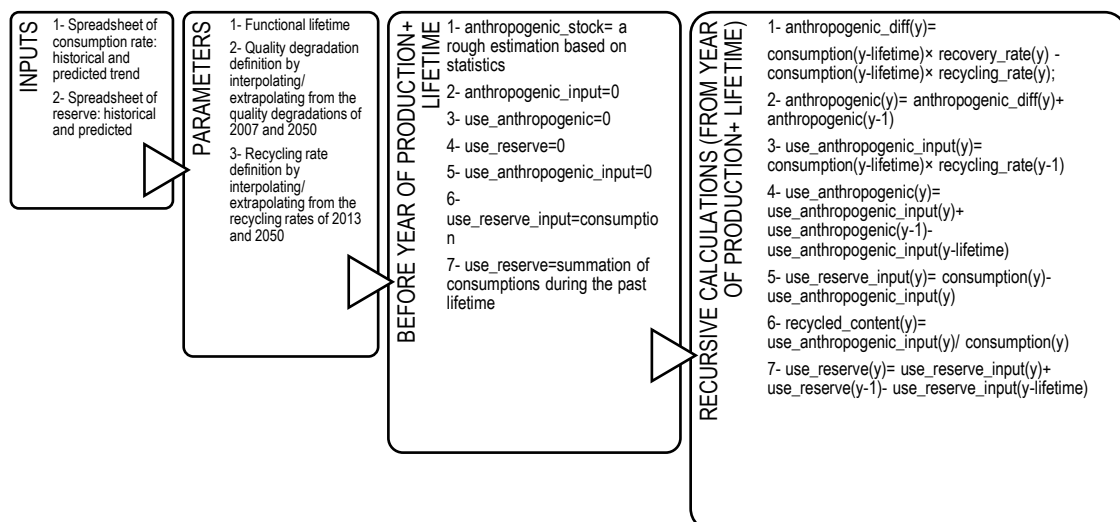


Figure 5-6 The stages of anthropogenic-based algorithm for predicting the indices for the future.

5.2.2 Assumptions and inputs of stability of production stock

A few decades after convergence of the population, the consumption will converge, too. This time, Figure 5-3 could be approached, considering a stable product stock. This means that the inputs to the product stock are equal to the outputs through the time. For solving it, an inverse problem is devised (Relation 5-1).

In this formulation, the content matrix (C) includes dimension of the Stock here called Flow to Stock ratio (F/S) (the transferred amount to the stock from which the transfer happens), geopolitical availability (GA) [148] and cross coefficients (CC).

All the indices are within the interval of [0, 10] except Flow to Stock where the real values are used. The Relation 5-1 means that in a specific situation, Flow to Stock, Geopolitical and Cross Coefficient, another variable exists, i.e. accessibility that affects the input and output product stock Flow (F). Therefore, multiplication of accessibility matrix by the content matrix, is Flow matrix. So, multiplication of Flow matrix by the inverse of content matrix gives the accessibility matrix. The characterization factors are defined by inverting of the accessibility. Therefore the (in)accessibility is expressed in inverse of mass.

$$Acc_{1 \times 3} \times C_{3 \times 3} = F_{3 \times 1} \quad \text{Relation 5-1}$$

$$[a_{use} \quad a_{res} \quad a_{rec}] \times \begin{bmatrix} \left(\frac{F}{S}\right)_{use} & GA_{use} & CC_{use} \\ \left(\frac{F}{S}\right)_{res} & GA_{res} & CC_{res} \\ \left(\frac{F}{S}\right)_{rec} & GA_{rec} & CC_{rec} \end{bmatrix} = [F_{use} \quad F_{res} \quad F_{rec}] \quad \text{Relation 5-2}$$

$$Acc_{1 \times 3} = F_{3 \times 1} \times C_{3 \times 3}^{-1}$$

$$(In)accessibility \text{ CFs are } 1/Acc_{1 \times 3} \left(\frac{1}{\text{unit of mass}} \right) \quad \text{Relation 5-3}$$

Substitution is an important parameter in defining the accessibility. Although the substitution is not applied to obtain the final accessibility parameter, a semi-quantitative assessment is proposed in the section 5.2.2.6.

5.2.2.1 The Geopolitical Availability Matrix (Short and Long Terms)

Geopolitical availability varies through the time. As an example, there are abundant REEs in the China while the Europe does not have economic reserves. But the European countries are continuously importing REEs within the REE-containing products. So, the REE-contaminated wastes are being deposited in the European countries, and in long-term, will have high-potentials for recovering REEs.

Geopolitical Availability is assessed for different stocks (reserve, product and recyclable). The reserve Geopolitical Availability is derived from Adibi et al (2016) [148]. Short-term and long-term reserve Geopolitical Availabilities are defined separately (Table 5-3). The Geopolitical Availability of the recyclable stock is always considered at the maximum, i.e. 10, as we consider no accessibility issue for the recyclable stock. This is justifiable: as most of the time the recyclable stock is filled in the same geographical zone as the market, i.e. near to product stock.

Table 5-3 Relations to calculate the Geopolitical Availability.

	Use	Reserve	Anthropogenic (recycling)
Geopolitical Availability Short term	$\frac{10}{\text{averagefunctionallifecycle}}$	$(GDI)=\sqrt[3]{F_{WGI} \times F_{\text{deviation}} \times F_{\text{countries}}}$	Completely accessible: 10
Geopolitical Availability Long term	$\frac{10}{\text{averagefunctionallifecycle}}$	$(DI)=\sqrt{F_{\text{deviation}} \times F_{\text{countries}}}$	Completely accessible: 10

$$GA = \left[\frac{10}{\text{functionallife}} \quad (G)DI \quad 10 \right] \quad \text{Relation 5-4}$$

5.2.2.2 Cross coefficient

The recovered materials are not necessarily pure. For example, iron and copper are mostly in alloys, and this composition makes recycling more complex. Also, some elements are mostly by-product of ore bodies, not the main element; e.g. silver is mostly byproduct in the iron mines. This phenomenon makes its production more difficult. The cross coefficient provides an estimation of the accessibility based on the cross effect

(alloy for recycling and by-product for the reserves) of elements in different stocks (reserve, product and recyclable). The range of the cross coefficients is the same as the accessibility matrix (0-10) because there is no priority between these two matrices.

5.2.2.3 Cross coefficient for reserve stock (main mining / by-product)

The reserve index is higher when an element is the main mining product. The coefficient (accessibility) is lower when the element is by-product of the mining of other elements. The cross coefficient of reserve is calculated, using the Metal Wheel, showing carrier metals and their co-elements as they occur in the ores naturally [53], [70]–[73].

5.2.2.4 Cross coefficient of recyclable stock

Cross coefficient of the recyclable stock is higher when an element is both the main recovered element and the element recovered with high share. The accessibility is lower when the element is more present in the mainly to benign low value products and mainly lost element. The cross coefficient of reserve is calculated, using the “Metal Wheel”, based on primary metallurgy but equally valid for metals recycling reflects the destination of different elements in base-metal minerals as the function of interlinked metallurgical process technology. Each slice represents the complete infrastructure for base- or Carrier-Metal refining. As there are so many different combinations of materials in End-of-Life products, only physics-based modelling can provide the basis for valid predictions. In essence, primary metallurgy is situated in a segment of complete processing plant, while the complexity of consumer product mineralogy requires an industrial ecological network of many metallurgical production infrastructures to maximize recovery of all elements in end-of-life products [53], [70]–[73]. Each column in Table 5-4 is multiplied by a corresponding decreasing factor, to reach the final cross coefficients of the iron, which are [1 5 10].

Table 5-4 Cross coefficients of the recyclable stock for Aluminium.

Al	Mainly Recovered Element	Mainly Element in Alloy	Mainly Element Lost
Primary Product	1		
Mainly to Pyrometallurgy		3	
Mainly to Hydrometallurgy			
Mainly to Benign Low Value		7	1

5.2.2.5 Flow to Stock ratio

Another influencing parameter is dimension of influencing stocks. The Flow to the Stock (F/S) ratio provides a relative measurement of the dimension of influencing stocks. The Flow is the input and output of the product stock (e.g. F_{RES} is the amount transferred from the stock of virgin material (reserve) to product stock). The stock is the amount available in a stock from which the transfer happens (e.g. S_{USE} equals to the product stock or S_{RES} equals to the Virgin material stock obtained from natural resources). The ratio represents the number of years to deplete the stock, assuming that the stock has no further inputs in the following years. The Flow and Stock is obtained on the stability year (2017). The values corresponding to the Flow and Stock are provided in ton in Table 5-5.

Table 5-5 Flow and Stock for the year of stability (2170) in ton.

In ton	Iron/ steel	Aluminum	Copper	Platinum	Cobalt	Silver	Dysprosium	Neodymium	Wood	Gravel/Sand
Stock use	2.54E+10	2.51E+09	6.43E+08	3.66E+03	1.82E+06	3.69E+05	2.26E+06	2.26E+06	6.18E+10	2.05E+12
Stock reserve	1.22E+11	6.50E+13	5.60E+12	1.10E+04	5.14E+06	3.85E+04	1.19E+08	1.19E+08	3.83E+11	2.45E+15
Stock recyclable	7.45E+10	3.59E+09	1.33E+09	1.82E+04	2.53E+05	7.14E+05	2.32E+07	2.32E+07	9.84E+10	5.09E+12

Stock losses (wastes)	1.97E+10	7.79E+08	5.12E+08	4.64E+03	5.77E+06	3.61E+05	5.43E+06	5.43E+06	1.38E+10	4.43E+11
Stock recycled	2.68E+09	1.03E+08	4.13E+07	4.46E+02	3.53E+05	7.80E+04	1.51E+05	1.51E+05	5.03E+08	1.55E+10
Stock virgin material	3.42E+08	2.38E+07	8.29E+06	1.07E+02	2.44E+04	1.88E+03	1.27E+05	1.27E+05	8.35E+08	3.26E+10
Transfer from use to recyclable (F_{USE})	1.64E+09	7.43E+07	2.72E+07	3.16E+02	1.80E+05	3.98E+04	1.85E+05	1.85E+05	9.94E+08	3.90E+10
Transfer from recycled to use (F_{REC})	1.34E+09	5.15E+07	2.06E+07	2.23E+02	1.77E+05	3.90E+04	7.57E+04	7.57E+04	2.52E+08	7.74E+09
Transfer from reserve to use (F_{RES})	3.49E+08	2.43E+07	8.46E+06	1.10E+02	2.49E+04	1.92E+03	1.30E+05	1.30E+05	8.52E+08	3.33E+10

5.2.2.6 Substitution

An input or factor of production can be substituted by another inputs for the same product. The substitution in some cases is systematic, and does not require additional efforts or costs, like in Iron. For other resources or in some applications, the substitution requires efforts and are less effective, like substitution of REEs; and in other cases the substitute of a resource is with performance loss or higher cost in specific functions, as platinum or cobalt.

To assess the substitution of a given resource precisely, the function of the resource has to be considered. Aluminum used in the aeronautic is not the same as that of in the construction. The most appropriate way of assessing the resource substitution is to assess them for different applications. To do so, there is a need to have a complete list of applications, the amounts of the materials which are used in each application and the sensitivity of the resource for each application.

Although we did not use input-output tables to assess the resource substitution index, the authors strongly suggest the use of these tables. For the purpose of this study, an average substitution factor is estimated based on the available data of substitution of different resources, in different applications [99]. The indices of the materials are defined based on the quantity of the materials used in different applications and they are weighted based on the substitution index, Table 5-6.

Table 5-6 Substitution index for different possible situations.

	Substitution index
substitution possible	10
substitutes are less effective	7.5
substitution with performance loss or higher cost	5
no satisfactory substitute	2.5

5.3 Results

5.3.1 Anthropogenic-based predictor

The anthropogenic-based predictor algorithm is applied on nine materials: iron (+steel), platinum, cobalt, copper, aluminum, wood, sand/gravel and REEs. The specifications, required for the predictor are summarized in the Table 5-7.

Table 5-7 Specifications of each material, used in the predictor. * For the wood, the resource is mentioned for 2015 since re-plantation may improve it. ** Precious metal.

Element	Iron/ steel	Platinum	Cobalt	Copper	Silver	Aluminum	Wood	Sand/ Gravel	Rare earth
Historic data years	1990-2015	1994-2015	1994-2015	1994-2015	1994-2015	1994-2015	1994-2015	1994-2015	1994-2015
Predicting years	2016-2170	2016-2170	2016-2170	2016-2170	2016-2170	2016-2170	2016-2170	2016-2170	2016-2170
lifetime years	27	11	9	22	9	33	55	55	11

Maximum resource (crust)	230 billion tons	100 million kilograms	25 million tons	6500 billion tons	1020 billion tons	55 to 75 billion tons	564 billion tons *	2457 billion tons	150 million tons
Quality degradation	98%	98%	98%	98%	98%	98%	98%	98%	98%
Recovery rate, 2007	87%	85%	68%	78%	98%**	85%	85%	85%	70%
Estimated recovery rate, 2050	92%	90%	78%	85%	98%**	90%	90%	90%	80%
Recycling rate, 2013	62%	50%	68%	46%	75% 2007 (UNEP)	49%	5%	1%	1%
Recycled content, 2007	37.5%	37.5%	37.5%	37.5%	37.5%	37.5%	-	-	5% (Nd and Dy)

The outputs of the algorithm for the iron and cobalt are shown in the Figure 5-7 and Figure 5-8, respectively. No reserve shortage is predicted till 2170, also the anthropogenic stock is getting close to the geological reserve (Figure 5-7-a). The relative increase of the recyclable stock to the reserve stock, results in the increase of the recycled content (Figure 5-7-b). The recycle content of the iron increases very fast, which shows the importance of recycling in the iron and steel industry.

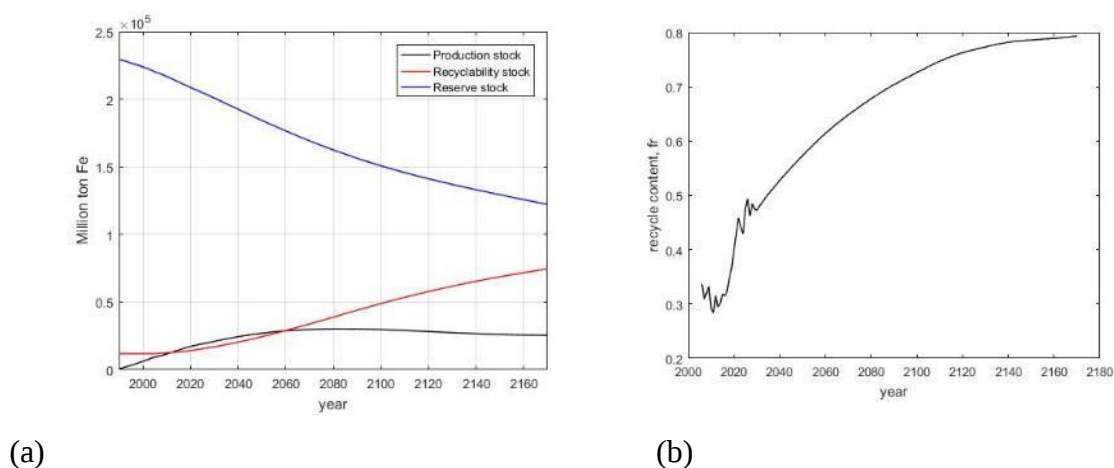


Figure 5-7 The output of anthropogenic predictor for the iron. a) The stocks of production, recyclability and reserve during the time. b) The prediction of the recycle content of the iron.

For cobalt there is no reserve shortage. But despite the iron, the anthropogenic stock does not increase that much. The reason is high recycling content which reaches to 90% in 2110.

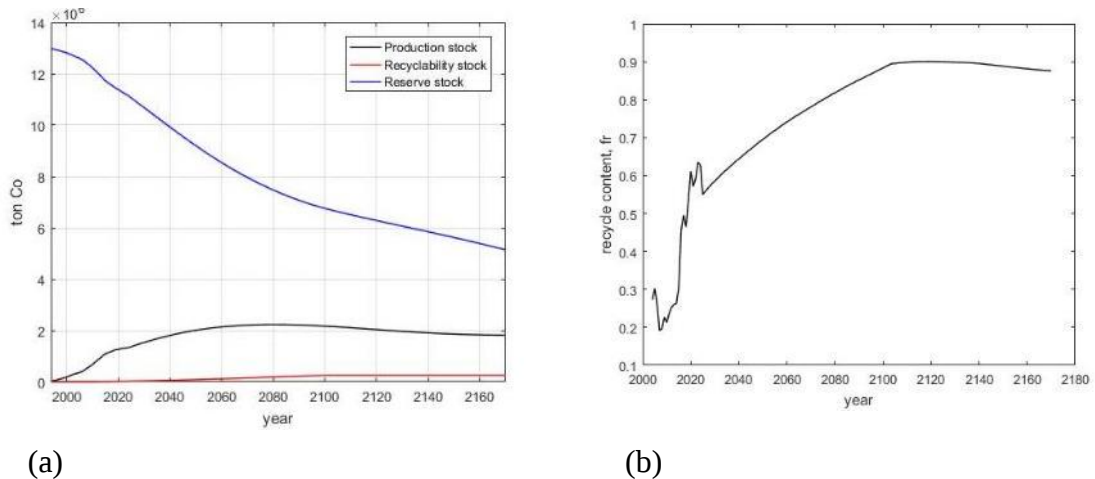


Figure 5-8 The output of anthropogenic predictor for the cobalt. a) The stocks of production, recyclability and reserve during the time. b) The prediction of the recycle content of the cobalt.

5.3.2 Stable product

Stable state is when the production stock remains constant; i.e. the summation of the input rates (extraction rate and recycled content) becomes equal to the summation of output rates (recovery rate and dispersion). For solving the problem (finding accessibility or inaccessibility in relation 5-2) in this state, Flow to Stock ratio, geopolitical availability and cross coefficients are firstly defined (Table 5-8). For the stock, it is necessary to find the year of which the curve of production is converged. The convergence year is fixed at 2170 since the production line is near horizontal.

Relation 5-2 is solved two times. In the first solution, accessibility is calculated whereas in the second time inaccessibility is found. All the coefficients of Table 5-8 are based on the provided assumptions. In-substitution is calculated by normalizing negative of substitution value between 0-10 except for the Flow/Stock where the real value is calculated then inversed (Stock/Flow).

Table 5-8 Expert-based values for solving relation 2 for stable-state of production stock.

		Time	Iron/steel	Aluminum	Copper	Platinum	Cobalt	Silver	Dysprosium	Neodymium	Wood	Sand and Gravel
Accessibility	Geopolitical availability Product	short	0.37	0.30	0.45	0.91	1.11	1.11	0.91	0.91	0.182	0.182
		long	0.37	0.30	0.45	0.91	1.11	1.11	0.91	0.91	0.182	0.182
	Geopolitical availability Reserve	short	4.96	6.47	6.87	2.32	4.81	6.07	4.79	5.23	8.32	7.93
		long	5.16	7.37	7.48	1.56	5.52	6.60	3.75	5.22	9.18	8.58
	Geopolitical availability Recyclable	short	10	10	10	10	10	10	10	10	10	10
		long	10	10	10	10	10	10	10	10	10	10
	Cross coefficient	PROD	1	1	1	1	1	1	1	1	1	1
		RES	5	5	5	2.5	5	2.5	2.5	2.5	10	10
		REC	10	4.4	8.4	8.5	8.4	7.5	5.2	5.2	10	4
	Stock to Flow ratio	PROD	2E+01	3E+01	2E+01	1E+01	1E+01	9E+00	1E+01	1E+01	6E+01	5E+01
		RES	9E+01	1E+06	3E+05	5E+01	3E+01	1E+00	2E+03	2E+03	2E+03	3E+05
		REC	2E+02	1E+02	2E+02	2E+02	1E+01	4E+02	2E+02	2E+02	1E+02	2E+02
	Substitution		10	10	10	5	5	10	7.5	7.5	10	7.5
Inaccessibility	Geopolitical availability Product	short	9.8	9.9	9.8	9.3	9.1	9.1	9.3	9.3	10.0	0.182
		long	9.8	9.9	9.8	9.3	9.1	9.1	9.3	9.3	10.0	0.182
	Geopolitical availability Reserve	short	5.2	3.7	3.3	7.9	5.4	4.1	5.4	5.0	1.9	7.93
		long	5.0	2.8	2.7	8.6	4.7	3.6	6.5	5.0	1.0	8.58
	Geopolitical availability Recyclable	short	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	10
		long	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	10
	Cross coefficient	PROD	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	1
		RES	5.2	5.2	5.2	7.7	5.2	7.7	7.7	7.7	0.2	10
		REC	0.2	5.8	1.8	1.7	1.8	2.7	5.0	5.0	0.2	5
	Flow to stock ratio	PROD	6.4E-02	3.0E-02	4.2E-02	8.6E-02	9.9E-02	1.1E-01	8.2E-02	8.2E-02	1.6E-02	1.9E-02
		RES	1.1E-02	7.9E-07	3.7E-06	2.0E-02	3.4E-02	1.0E+00	6.4E-04	6.4E-04	6.6E-04	3.2E-06
		REC	4.7E-03	6.8E-03	6.3E-03	6.0E-03	9.9E-02	2.7E-03	5.6E-03	5.6E-03	8.7E-03	6.5E-03
	In-substitution		0.2	0.2	0.2	0.2	5.2	5.2	0.2	2.7	2.7	0.2

The obtained results of reserve values by inaccessibility in Fe-eq are shown and compared in Figure 5-9 with CML Fe-eq characterization factors to reveal how the CF varies, using different indicators. The reserve inaccessibility is very close in definition to resource impact assessment methods.

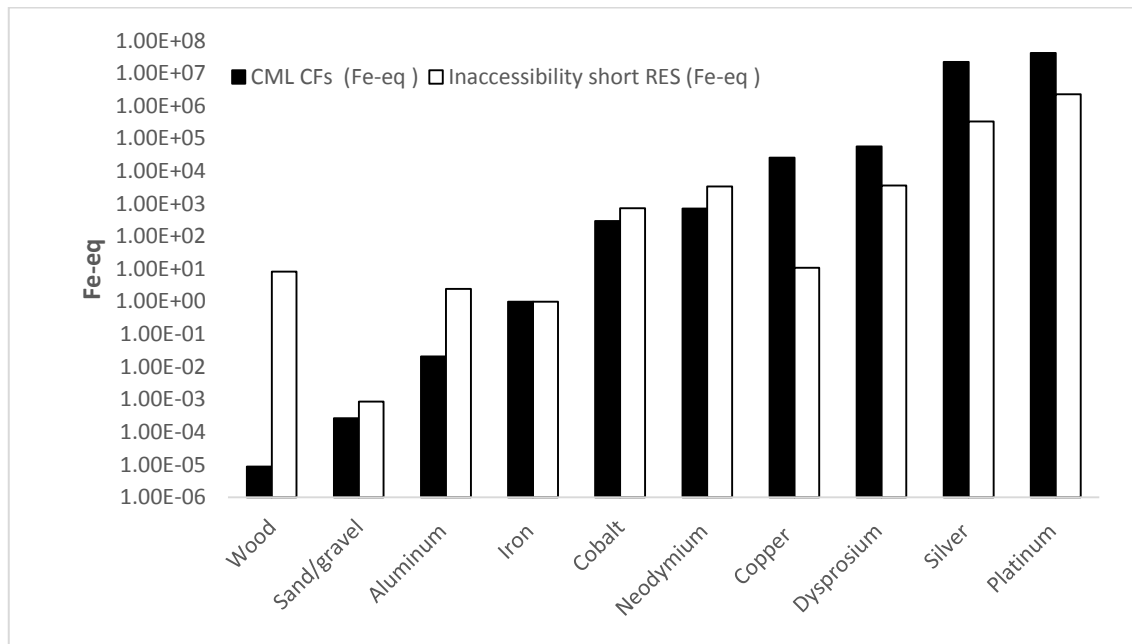


Figure 5-9 CFs variation in short -term Inaccessibility Reserve compared to CML.

Compared to CML, the order of importance of resources changes in the developed method. It is found that most of resources are highly influenced by introduction of other indicators. Copper, Silver, Dysprosium and Platinum have low impacts while resources like Neodymium, Cobalt, wood, Sand and gravel and Aluminum have high impacts.

Finally, calculating the short- and long-term accessibility matrices by inverse solution, Relation 5-3, is given in Table 5-9. Recycling and reserve of the platinum are the least accessible, then REEs. But recycling of cobalt is the least accessible in long-term. Iron and Gravel are the most accessible materials both in short- and long-term in reserve and recycling. Sand and gravel has higher impact of Recycling compared to reserve extraction. After the platinum, REEs are least accessible materials.

Table 5-9 Inaccessibility and Accessibility indices (short term). The output of steady-state solution. The units are converted all to equivalent to the production in ton.

Stock		Iron/steel, ton	Aluminum, ton	Copper, ton	Platinum, ton	Cobalt, ton	Dysprosium, ton	Neodymium, ton	Ag, ton	Wood, ton	Gravel and Sand, ton
Accessibility	PROD	6.1E-10	5.5E-07	7.0E-08	3.5E-03	2.6E-06	3.3E-05	5.8E-06	5.8E-06	1.2E-09	3.1E-11
	RES	8.4E-10	1.4E-03	2.3E-03	3.6E-03	6.4E-06	9.2E-05	1.8E-03	1.8E-03	2.7E-08	1.8E-07
	REC	2.5E-09	2.0E-07	3.7E-07	1.7E-02	2.0E-05	1.6E-03	1.3E-04	1.3E-04	2.4E-08	5.4E-09
Inaccessibility	PROD	1.4E-09	4.7E-10	2.5E-09	2.0E-04	8.8E-08	4.5E-05	4.6E-07	4.7E-07	3.7E-10	2.6E-13
	RES	7.2E-11	1.8E-10	7.9E-10	1.7E-04	5.2E-08	2.4E-05	2.6E-07	2.4E-07	5.9E-10	6.1E-14
	REC	2.6E-12	5.7E-10	6.1E-10	2.9E-03	3.4E-07	2.3E-05	5.4E-07	4.2E-07	8.4E-12	1.9E-13

The general key in interpreting the results of Table 5-9 is that accessibility values show high potential and inaccessibility values represent the problems and threats. So, interpreting reserve values by inaccessibility and recycling values by accessibility as discussed in 5.1.3 are reasonable. As an example, the REEs show higher values of recycling accessibility so they have high recycling potentials and makes it worth investigating. In the meantime, inaccessibility of their reserves is less problematic. It means that there are few but not major difficulties and problems in their reserves accessibility. Another example is platinum which has high reserve inaccessibility value; i.e. difficulties in reserve accessibility, meanwhile high recycling potential (due to the high accessibility). Reversely for the gravel both the reserve and the recycling is not that

much promising, as their recovery is very complex and their quality degradation is significant.

In order to illustrate the different influencing factors on accessibility and inaccessibility, the (in)accessibility values which are provided in Table 5-9 are divided by the corresponding flows (transfer to the corresponding stock) and illustrated in Figure 5-10. As illustrated in the Figure 5-10 resources like Silver, Gravel and Sand, Aluminum and Rare Earth Elements represents the highest recycling impact. With regard to the affecting parameters (content matrix) on the accessibility of resources in earth's crust the highest impact is on Cobalt, Gravel and Sand, Aluminum, Copper, Platinum, Rare Earth Elements and Iron/steel.

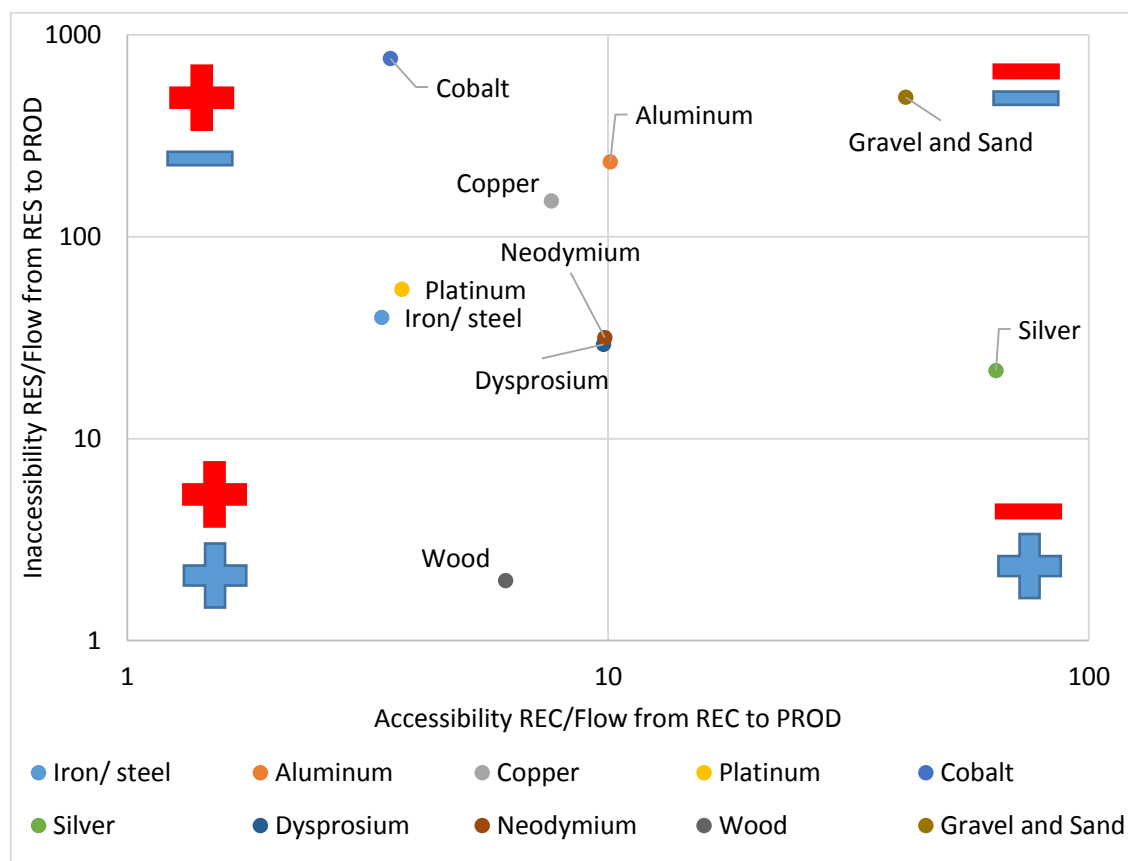


Figure 5-10 The affecting ratio on reserve and recycling ((in) accessibility/Corresponding Flow).

5.4 Case study: LCA of wind turbines

Datasets of four different types of wind turbine 2.5 MW were extracted from SimaPro Software. A wind turbine can be made of iron, concrete or hybrid. Each type, either contains either REEs (DDPMG) or does not (DFIG). Different wind turbines scenarios are provided in Table 5-10 and their respective composition is provided in Table 5-11. All quantities are converted to kg. For wood, the density is assumed to be 700 kg/m³. These quantities are multiplied by the proposed characterization factors, and provided in Table 5-12.

Table 5-10 Scenarios of different wind turbines studied.

Scenario 1: DFIG Iron	Double Fed Induction Generator, towers made of Iron
Scenario 2: DDPMG Iron	Direct-Drive Permanent Magnet Generator, towers made of Iron
Scenario 3: DFIG Concrete	Double Fed Induction Generator, towers made of Concrete
Scenario 4: DDPMG Concrete	Direct-Drive Permanent Magnet Generator, towers made of Concrete

Table 5-11 Composition of different types of wind turbines. *copper is used as winding wires (so recyclable).

	DFIG Iron	DDPMG Iron	Unit	DFIG Concrete	DDPMG Concrete	Unit
Cobalt	1.13	1.07	g	450	392	mg
Iron	325	303	t	101	79.7	t
Aluminum	6.88	6.52	t	6.35	5.98	t
Copper*	5223	5714	kg	5021	5520	kg
Silver	3.55	3.86	g	2.11	2.41	g
Wood	22.45	22.35	m ³	10.4	10.52	m ³
Sand	38.6	45.7	kg	36.1	43.2	kg
Gravels	1220	1210	t	1440	1430	t
Dysprosium	0	5.52	kg	0	5.52	kg
Neodymium	0	276.08	kg	0	276.08	kg

Table 5-12 Results of impact assessment based on CFs for different wind turbines. (Short- and long-term)

Wind turbine (Different types)	Accessibility Recycling (1/mt)	Inaccessibility Reserve (1/mt)
DFIG Iron	3.82E-08	1.11E-05
DDPMG Iron	1.06E-07	4.76E-05
DFIG Concrete	1.68E-08	1.13E-05
DDPMG Concrete	8.45E-08	4.79E-05

Figure 5-11 illustrates the results inaccessibility and accessibility values for four different types of Wind turbines (DFIG and DDPMG / Iron and concrete) done in this case-study. According to Figure 5-11, Wind turbines with REEs (DDPMG) have much higher impact with regard to recycling and reserve.

The concrete technologies has higher recycling accessibility impact (due to the high impact of sand and gravel) while iron technologies are higher in impact with regard to inaccessibility reserve values.

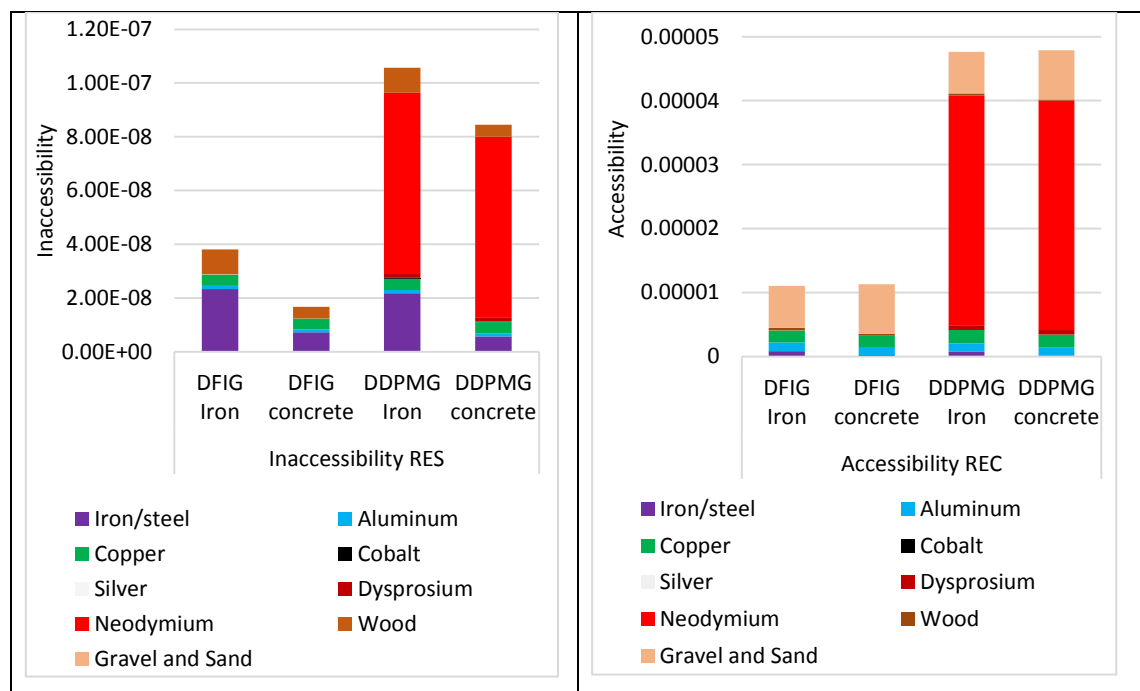


Figure 5-11 Comparison between four different types of Wind turbines for a) Accessibility of recycling and b) inaccessibility of reserve and the contribution of different resources.

Figure 5-11 furthermore compares the inaccessibility of the DFIG and DDPMG (concrete) scenarios and shows the contribution of different resources. The main contributors to the inaccessibility are the Rare Earth Elements (Neodymium -DDPMG), Iron, Copper, and wood. The highest impact with regard to accessibility recycling is due to the Neodymium when comparing the two technologies and Sand and gravel.

5.5 Discussions

Assessing “Anthropogenic-based prediction” and “Accessibility-stable effects” together with sector applications of resource, can help us propose different decision making solutions when dealing with products and services.

A shift to alternative resources may be the priority when:

- a) Resources are identified with both reserve and recycling issues e.g. Platinum, REEs.
- b) Low-moderate functional life resources are used in high functional life applications (and vice versa).

A change/adjustment in the design may be the priority when:

- a) Resources (although applicable to all resources) are used in low-moderate functional life (and corresponding sectors e.g. electronics, automotive).
- b) Resources used in products with recycling complexities (simplify the dismantling).

A development in the recycling sectors may be the priority when (improve collect and sorting):

Resources with high recyclable stock available (e.g. REEs, Sand and gravel) in anthropogenic stock.

5.6 Conclusion

Resource assessment and circular economy are subjects in the areas of business, governmental and research contexts, which have been gaining more attention and facing big challenges in their way to growth. In this work, a new method providing a comprehensive approach to assess the accessibility of resources is presented, which is mainly based on the concept of circular economy. The parameters Geopolitical availability, Cross Coefficient and Substitution should be defined.

The method goes beyond the simple geographical availability. A comprehensive assessment is made on different life cycles. The approach calculates the accessibilities of the reserve, recycling and product stocks, separately. The accessibility and inaccessibility as a positive and negative indicator, highlights potential positive and negative points of different resources with regard to extraction, recycling and use. The accessibility index covers all types of resources (renewables and non-renewables).

- The new method is developed based on the material circulation during their life cycles. The results may be used to empower the use of LCA in a comprehensive resource assessment. The method is developed also in support of future studies and decision making through the framework of circular economy. Also, it may be used as a hybrid approach to reinforce the link between LCA and circular economy, as well as to calculate resource Characterization Factors based on two prospective: accessibility and inaccessibility.

In addition, the proposed multi-indicator modeling resource circulation in economy, results in identifying new resources as hotspots. REEs show high impact both with regard to reserve and recycling. Resources (e.g. sand/gravel) show contrasting effect in term of extraction and recycling.

We would like to highlight that the proposed method and characterization factors are to be used considering the assumptions made in this chapter. Improvements are recommended to increase the effectiveness and efficiency of the proposed method and the characterization factors:

- Product (In)accessibility is relevant to be interpreted. The results for both indicators (related to the Product Stock) are developed but not assessed in this work.
- Sensitivity assessment on different accessibility parameters may help to demonstrate the validity and preciseness of different influencing parameters. And as consequence, to improve the method and to make the results more coherent.
- Input parameters and assumptions need to be improved. E.g. quality degradation as introduced in model is considered to be constant for all resources while the ration needs to be assessed for each resource.
- Finally more case studies are needed to challenge the results.

In this research project, I tackled different issues related to the resources in LCA and Circular Economy as follows:

- 1- REEs are among resources with a relatively high resource depletion potential, therefore they are essential to be included in the assessment of resource depletion impact. The characterization factors I developed in chapter 3 provide for the first time, the resource depletion for very strategic REEs resources based on two widely-used LCA impact assessment methodologies in Europe, i.e. CML and ReCiPe. The gathered data on these resources are used in chapters 4 and 5 as an input for newly developed methods. The REEs CFs are useful to be implemented in the main LCA software such as Simapro and GaBi in order to address the issue of the resource depletion of the REEs.
- 2- The second major issue, discussed in my work, is the conceptual issues behind existing LCIA methods. The LCIA resource methods are not developed to be used for all types of the resources. As an example, in the CML method, only extraction rate of a resource and available reserve are considered, while regeneration rate (related to the biogenic resources) is overwhelmed. Therefore, the concepts behind different resource depletion characterization methods need to be revised. Given the fact that, resource assessment in LCA are based on limited parameters, I suggest in the current work that there is a need to go beyond the current LCIA method in order to incorporate other important factors (e.g. recycling, geopolitical availability, substitution, etc.), not yet covered by the LCA resource assessment methods.

Accordingly, new Characterization Factors are developed in chapter 4, taking into account different criteria, which affect the availability of resources through different life cycles. Global Resource Indicator, as I proposed in chapter 4, integrates resource assessment aspects to better characterize resources. Both recyclability and criticality of resources are taken into account to model scarcity of resources more comprehensively. The methods proposed in this work including the Global Resource Indicator, may cover all types of resources (renewables and non-renewables). Data needed to develop the missing additional characterization factors are quite simple to

be provided. Therefore, gaps may be filled compared to the existing LCA resource assessment methods.

- 3- LCA with its current indicators fails to provide an applicable material-product management decision making resource indicator, based on potential Circular Economy benefits, of different resources. A value-oriented non-monetary resource indicator was developed in the 5th chapter where the potential (or importance) of different resources with regard to Circular Economy are reflected. Two main indicators are obtained at the consumption constant level. The first one is applicable at the natural resource extraction level and the second one is applicable to recycling (Circular Economy) level. For natural resource extraction, the inaccessibility is assessed, which means less available resources at extraction level leads to higher inaccessibility impact. Regarding the Circular Economy indicator, more accessibility of recyclable resource leads to higher impact. This means that, the more accessible recyclable stock is, there is more potential to utilize them as the recycled content in the product (or less recycled content feeds the use phase). Therefore the final impact of a resource is higher when its accessibility of recycling is higher.

Three main indicators are established to define the inaccessibility and accessibility of natural resources and recyclable resources introduced in the content matrix (C): dimension of the Stock here, called Flow to Stock ratio (F/S) (the transferred amount divided by the stock from which the transfer happens), geopolitical availability (GA) [148] and cross coefficients (CC).

The new indicator, I propose in chapter 5, is based on the material circulation during its life cycles. The indicator may be used as a new consistent approach to empower the use of LCA in a comprehensive resource assessment. The method supports decision making through framework of circular economy and may be used to reinforce the link between LCA and circular economy and to provide the resource Characterization Factors based on the both prospective.

6.2 Outlook

6.2.1 Resource prospective versus other approaches

The resource issue may be assessed based on two major points of view, accessibility and inaccessibility of resources. The accessibility indicator as proposed in this work, focuses on positive resource availability, highlighting the most attractive potential points over resources life cycles. These approaches focus more on the upstream resource cycle, including Reserve, Production and Recyclable stocks and the transfer coefficient between them. The aspects, affecting transfer coefficient between these compartments may be assessed through a set of parameters like, substitution, cross coefficient and geopolitical availability.

In LCA, the damages caused by human activities are measured. Therefore LCA considers the resource problem based on downstream prospective. The best approach may be to associate the resource impact to waste, dissipative losses and effects of waste generation. However, all resource assessment methods in LCA has hitherto focused only on extraction, while it may be more reasonable to consider losses. This issue becomes more considerable when recycling technologies become more effective. In this work, in order to assess the damage, we measured the inaccessibility by inverting the transition coefficients. I suggest that the pathway in the future LCA resource research projects may be focused on the downstream resource aspects, more specifically on the losses in different life cycles.

6.2.2 Use of input-output tables

I recommend the use of input-output tables to improve the resource assessment. In general the advantage to use input-output tables is the fact that they bring focus at sector or even to sub-sector level where associating complex aspects are more likely to be feasible. As an example substitution or quality degradation of iron, aluminum, sand and gravel, or wood are more likely to be assessed in construction sector than in the overall

economy. Involving the functions in a “correct” proportion using the input output table can be solved without entering any allocation procedure [151].

I recommend the use of input-output tables also to elaborate some modeling parameters. As an example, the service life of materials, derived from their consumption in product groups may be improved, using input-output tables, linking the products to the material consumption. Also indicators, like substitution, need to be improved based on the consumption of resources in different applications. Using input-output tables may permit development of regionalized resource indicators. In that case, indicators, related to the criticality of the resources may be adapted based on regional criticality of resources, e.g. localized due to European standards.

In general the proposed method uses different input parameters. I suggest the improvement of different parameters. Also research projects may be defined for development of these parameters to be implemented in the future for updating CFs.

A- Appendices

A1- The CFs of REEs for the CML and ReCiPe methods, based on the REEs prices in 2013, and the average price within five years from 2009 to 2013 in kg Fe-eq

The prices of REEs and iron are the base information to make the calculations in the ReCiPe method

Table A-1 and

Table A-2. Two different values are used in this study:

- (i) The price of REEs in 2013, and
- (ii) The average price within five years from 2009 to 2013. (Because of very high fluctuations in the price of these elements, it is decided to include a sensitivity analysis, using five-year average prices.)

Table A-1 Prices "Vc" are extracted from BCC research and metalprices.com. * Data not available, the average is considered as proxy.

OXIDE	Vc (2013) \$/kg	Avg Vc \$/kg
Lanthanum	3.71	42.65
Cerium	3.96	43.35
Praseodymium	94.08	92.8
Neodymium	52.81	101.475
Samarium	3.05	51.825
Europium	759.22	1711.5
Gadolinium	27.32	75.925
Terbium	561.16	1536.25
Dysprosium	288.83	757.25
Holmium	180.40*	2623.333
Erbium	180.40*	165.8667
Thulium	180.40*	3986
Ytterbium	180.40*	293.8
Lutetium	180.40*	3026.667
Yttrium	9.90	69.325

Table A-2 The CFs of REEs for CML and the ReCiPe methods, based on the REEs prices in 2013, and the average price within five years (2009-2013), in kg Fe-eq.

Resources	ReCiPe 2013	ReCiPe avg Vc	CML
Lanthanum	1.76E-01	2.32E+01	4.36E+02
Cerium	3.73E-01	4.47E+01	2.10E+02
Praseodymium	2.26E+01	2.20E+01	2.08E+03
Neodymium	2.33E+01	8.61E+01	7.21E+02
Samarium	7.26E-03	2.09E+00	1.10E+04
Europium	8.95E+01	4.55E+02	7.33E+04
Gadolinium	2.96E-01	2.29E+00	1.84E+04
Terbium	1.56E+01	1.17E+02	9.11E+04
Dysprosium	1.81E+01	1.24E+02	5.68E+04
Yttrium	1.34E-01	6.57E+00	1.16E+04
Fe	1.00E+00	1.00E+00	1.00E+00

A2- NdFeB permanent magnet inventory

The inventory is provided for production of 1 kg of cradle to gate NdFeB permanent magnets in China. The reference year is 2015. No official approval by producer or operator on the provided inventory. The data set represents the applied technology with a good data quality in overall. The inventory is based on industrial and literature data. The losses (27%) for all processes from the mining to the final production are included in the assessment. The losses are modelled when closed loop recycling exists as an input, and as wastes when they are landfilled. Electricity and particulate emissions provided in Table A-3 correspond to the processes from strip casting to the annealing Figure A-1. All the resource and emissions from extraction and mining are part of the processes included in the material inputs. The inventory is cradle to gate and the downstream processes (E.g. End-of-Life) is not considered. The below process is modelled as part of the inventory:

- REE concentrate production, 70% REO, from Bastnaesite China,
- REE oxides production from Bastnaesite concentrate in China. The resource inputs from the earth are adjusted in the database to correspond to the NdFeB permanent magnets, including the losses,
- Production of pig iron,
- Production of Boric oxide,
- Production of other minor additions of transition metals,
- Electricity consumption for the below processes, using China medium voltage electricity mix
 - Strip casting process
 - Hydrogen decrepitating
 - Jet mill
 - Aligning and pressing in magnetic field
 - ISO static press
 - Sintering
 - Annealing

Figure B1 and Table B1 provide respectively the system boundary and the corresponding life cycle inventory inputs for 1 kg of NdFeB (32%/66%/1%) permanent magnet. The inventory, is derived from [121], and completed by specific industry data from China.

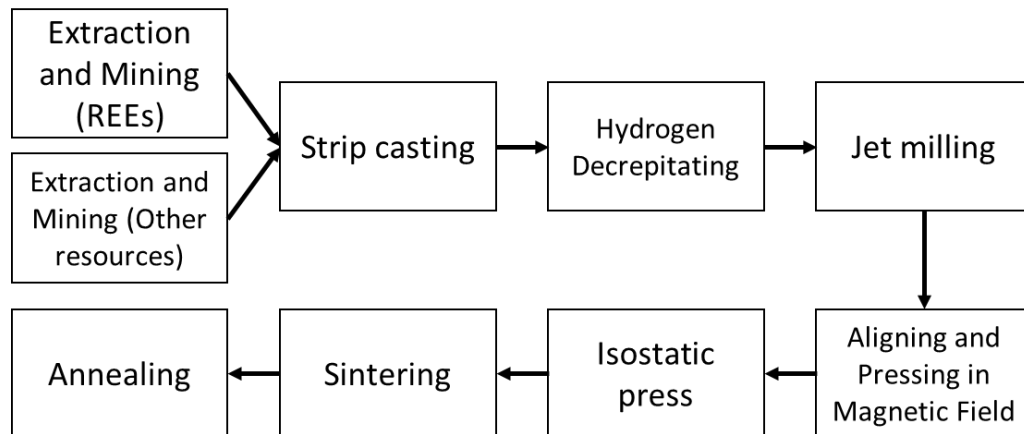


Figure A-1 System boundary for 1 kg of NdFeB (32%/66%/1%) permanent magnet.

Table A-3 Life Cycle Inventory inputs for 1 kg of NdFeB (32%/66%/1%) permanent magnet.

Product		
Permanent magnet NdFeB (32%/66%/1%)	1.00E+00	kg
Materials/fuels		
Pig iron {GLO} production Alloc Rec, U	8.67E-01	kg
Neodymium oxide {CN} rare earth oxides production from bastnasite concentrate for magnet	4.21E-01	kg
Boric oxide {GLO} market for Alloc Rec, U	1.31E-02	kg
Aluminium, primary, ingot {CN} production Alloc Rec, U	5.47E-04	kg
Copper {RoW} production, primary Alloc Rec, U	1.51E-04	kg
Cobalt {GLO} production Alloc Rec, U	1.09E-03	kg
Electricity/heat		
Electricity, medium voltage {CN} market for Alloc Rec, U	2.52E+00	kWh
Emissions to air		
Particulates, unspecified	3.00E-02	kg

A3- ReCiPe End-point Characterization Factors (CFs)

The end- point characterization factors are calculated by marginal cost increase per dollar by equation:

$$CF_{c.kg.end} = MCI_{c.kg.} \times P_{c.kg.} \times NPV_T = -4x \times \frac{\bar{M}_c}{(c_c)^2} \times V_c^2 \times P_{c.kg} \times NPV_T$$

End-point CFs are provided in Table A-4 based on different discount rates.

Table A-4 ReCiPe End-point Characterization Factors (CFs) of REEs, using 2013 prices.

		Vc (2013)		surplus costs or discount rates				
		Mid-point	Fe eq	X	2%	3%	4%	5%
LREO	Lanthanum	7.26E-03	1.76E-01	17.21	0.510	0.515	0.520	0.526
	Cerium	1.54E-02	3.73E-01	17.21	1.083	1.094	1.105	1.117
	Praseodymium	9.35E-01	2.26E+01	17.21	65.675	66.352	67.043	67.749
	Neodymium	9.64E-01	2.33E+01	17.21	67.686	68.384	69.096	69.823
	Samarium	3.00E-04	7.26E-03	17.21	0.021	0.021	0.022	0.022
HREO	Europium	3.70E+00	8.95E+01	17.21	259.587	262.263	264.995	267.785
	Gadolinium	1.22E-02	2.96E-01	17.21	0.858	0.867	0.876	0.885
	Terbium	6.44E-01	1.56E+01	17.21	45.216	45.682	46.158	46.644
	Dysprosium	7.46E-01	1.81E+01	17.21	52.427	52.968	53.520	54.083
	Holmium	3.57E-02	8.64E-01	17.21	2.505	2.531	2.557	2.584
	Erbium	1.38E-01	3.35E+00	17.21	9.714	9.814	9.916	10.020
	Thulium	1.99E-02	4.82E-01	17.21	1.397	1.411	1.426	1.441
	Ytterbium	1.48E-01	3.58E+00	17.21	10.386	10.493	10.602	10.714
	Lutetium	2.68E-02	6.50E-01	17.21	1.884	1.904	1.924	1.944
	Yttrium	5.54E-03	1.34E-01	17.21	0.389	0.393	0.397	0.401
	Fe	4.13E-02	1.00E+00	1.30E-02	0.002	0.002	0.002	0.002

A4- Substitutability of some resources.

Table A-5 Substitutability of some resources.

Resource	Substitute
Iron	-Aluminum and plastics, in the motor vehicle industry. -Aluminum, concrete, and wood in construction. -Aluminum, glass, paper, and plastics in containers.
Aluminum	-Glass, paper, plastics, and steel can substitute aluminum in packaging. -Magnesium, steel, and titanium can substitute aluminum in ground transportation and structural uses. -Composites, steel, vinyl, and wood can substitute aluminum in construction. -Copper can replace aluminum in electrical and heat-exchange applications.
Copper	-Aluminum substitutes copper in power cable, electrical equipment, automobile radiators, and cooling and refrigeration tube. -Titanium and steel are used in heat exchangers; optical fiber substitutes copper in telecommunications applications. -Plastics substitute copper in water pipe, drain pipe, and plumbing fixtures.
Sand and gravel	-Crushed stone is often substituted natural sand and gravel. -Recycled asphalt and Portland cement concretes are being substituted by virgin aggregate
Wood	- Reinforced concrete and steel structures can substitute the wooden constructions.
Silver	- Surgical pins and plates may be made with tantalum and titanium in place of silver. - Stainless steel may substitute silver flatware. -Aluminum and rhodium may be used to replace silver that was traditionally used in mirrors and other reflecting surfaces.
Platinum	-Palladium has been substituted by platinum in most gasoline-engine catalytic converters and diesel catalytic converters.
Rare Earth	-Substitutes are available for many applications but are generally less effective

A5- Substitution factor

An input or factor of production, given sufficient time for adjustment and sufficient resources to effect the change, can be substituted by other inputs to produce the same output.

Production factor could be modified or adjusted. In this section, we developed substitution factors for building sector. Noteworthy that these factors should be specified for each sector, separately. To facilitate calculations, we consider the major products used in the buildings, and we mark 1 if the resource is used in the product, otherwise 0. More insight is given to a potential future development of the substitution based on input-output economic tables for a specific geographic scope in Chapter 4. Table A-6 shows the mostly used resources in different parts of building sector.

Table A-6 Resources, used in different parts of building sector.

	Foundations	beams	windows	glass	doors	walls	tiles	isolation	electric circuits	roofing	siding	Wind turbine
IRON	1	1	1	0	1	1	0	0	1	1	0	1
ALUMINIUM	0	0	1	0	1	0	0	0	1	0	0	1
COPPER	0	0	0	0	0	0	0	0	1	0	0	1
SAND AND GRAVEL	1	1	0	1	0	1	1	1	0	1	1	1
SILVER	0	0	0	0	0	0	0	0	1	0	0	1
Cobalt	0	0	0	0	0	0	0	0	0	0	0	1
Dysprosium	0	0	0	0	0	0	0	0	0	0	0	1
Neodymium	0	0	0	0	0	0	0	0	0	0	0	1
Europium	0	0	0	0	0	0	0	0	0	0	0	0
Platinum	0	0	0	0	0	0	0	0	0	0	0	0
WOOD	1	1	1	0	1	1	1	1	0	1	1	1

Based on provided values in each column, the substitution factor of the resource is calculated. At first, the resource-application value is divided by the total resources in the corresponding application. One minus this value is multiplied by 100 providing

substitution percent for each resource in each application. For a given resource, the final substitution is the average of this value in all building applications.

E.g. the iron in "Foundations" has substitution factor of $(1 - \frac{1}{1+1+1}) \times 100\% = 66.67\%$. The substitution factor of iron resource in the building sector is estimated by averaging (Table A-7).

Table A-7 Substitution factors of resources in the building sector.

	Substitution factor (S)
IRON	80.32%
ALUMINUM	91.44%
COPPER	96.99%
SAND AND GRAVEL	67.13%
Silver	96.99%
Cobalt	99.07%
Dysprosium	99.07%
Neodymium	99.07%
Europium	100%
Platinum	100%
WOOD	68,18%

"Sand and gravel" seems to be the most irreplaceable resource in the building sector, while substitution factor of copper is about 97% since it is used in low quantities, only in electric circuits.

The GRI as presented in chapter 4 (Relation 4-1) may be adjusted to include the substitution. The formula to calculate the GRI CFs of resources, including the substitution is provided:

$$GRI = \left(\frac{X}{Y \times Z} \right) \times S$$

$$GRI_{Fe-eq} = \left(\frac{F_{CML}^{normalized}}{(1 - F_{dispersion}) \times 10 \times F_{recycling} \times \sqrt[3]{F_{WGI} \times F_{deviation} \times F_{countries}}} \right) \times S$$

$$\times \frac{F_{recycling}^{Fe} \times (1 - F_{dispersion}^{Fe}) \times 10 \times \sqrt[3]{F_{WGI}^{Fe} \times F_{deviation}^{Fe} \times F_{countries}^{Fe}}}{S_{Fe-eq}}$$

The substitution in this approach is assessed at sector level. Therefore the adjusted GRI will be sector based (in this annex building and construction). As consequence the use of input-output tables is recommended by the authors.

A6- Anthropogenic-based algorithm for predicting the indices for the future

```

for y=consumption(1,1)+flife+1:yearE
    i=i+1;
    j=j+1;
    AnthDiff(i,:)=[y consumption(consumption(:,1)==y-flife,2)*recov(recov(:,1)==y,2)-...
        consumption(consumption(:,1)==y-flife,2)*recycl(recycl(:,1)==y,2)];
    Anth(i,:)=[y Anth(i-1,2)+AnthDiff(i,2)];
    AnthInp(i,:)=[y consumption(consumption(:,1)==y-flife,2)*recov(recov(:,1)==y,2)];
    UseAnthInp(i,:)=[y consumption(consumption(:,1)==y-
flife,2)*recycl(recycl(:,1)==y,2)*qual(qual(:,1)==y,2)];
    UseAnth(i,:)=[y UseAnth(UseAnth(:,1)==y-1,2)+UseAnthInp(UseAnthInp(:,1)==y,2)-...
        UseAnthInp(UseAnthInp(:,1)==y-flife,2)];
    UseResInp(i,:)=[y consumption(consumption(:,1)==y,2)-
UseAnthInp(UseAnthInp(:,1)==y,2)];
    RecyclCont(j,:)=[y
UseAnthInp(UseAnthInp(:,1)==y,2)/consumption(consumption(:,1)==y,2)];
    UseRes(i,:)=[y UseRes(UseRes(:,1)==y-1,2)+UseResInp(UseResInp(:,1)==y,2)-
UseResInp(UseResInp(:,1)==y-flife,2)];
    totalExt=UseResInp(i,2)+totalExt;
    Use(i,:)=[y UseAnth(i,2)+UseRes(i,2)];
    Rese(i,:)=[y max(res(:,2))-totalExt];
    if Rese(i,2)<0; Rese(i,2)=0;
    end
    WasteT=WasteT+consumption(consumption(:,1)==y-flife,2)*(1-
recov(recov(:,1)==y,2))+...
        consumption(consumption(:,1)==y-flife,2)*recycl(recycl(:,1)==y,2)*(1-
qual(qual(:,1)==y,2));
end

```

A7- Example of assessment of Cross coefficient of recyclable stock for Aluminum.

T: The total score is obtained by multiplying, number of times a resource is present in table by 100 then multiplied by 2. Example for Al $12 \times 2 \times 100 = 2400$.

X1: Primary Product, Mainly to Pyrometallurgy and Mainly Recovered Element are multiplied by 100 once summed within lines and columns. Example for Al $4 \times 100 = 400$.

X1: If $I_{(\text{Primary Product Mainly Recovered Element is equal})}$ to 1 then a bonus of sum of Mainly to Pyrometallurgy, Mainly to Hydrometallurgy and Mainly to Benign Low Value is multiplied by 50 after summation within the lines. Example for Al $11 \times 50 = 550$.

X3: Mainly to Hydrometallurgy and Mainly Element in Alloy are multiplied by 10 once summed within lines and once within columns. Example for Al $0 + 100 = 100$.

X4: Mainly Element Lost and Mainly to Benign Low Value Products are multiplied by 1 once summed within lines and once within columns. Example for Al $8 + 1 = 9$.

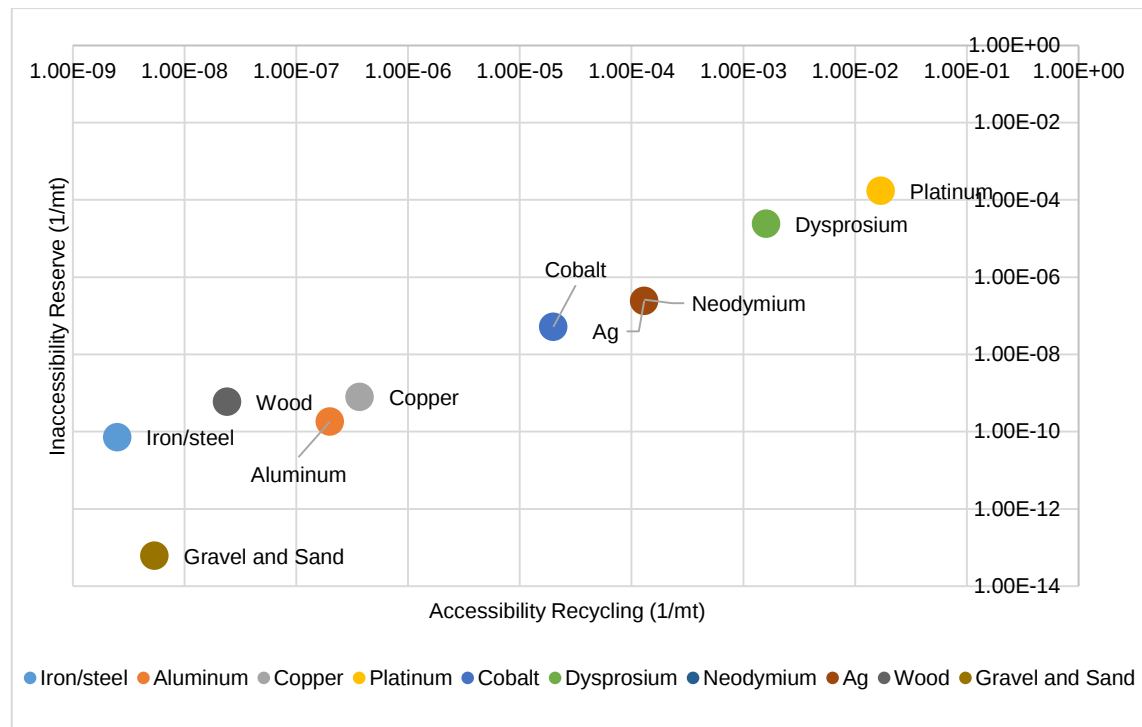
Then the Cross coefficient of recyclable stock for Aluminum is equal to $(X1 + X2 + X3 + X4)/T$. Example for Al Cross coefficient = $1059/2400 = 0.44125$.

This means if the element is only present Mainly in Recovered Element or Mainly to Pyrometallurgy and Primary Product then the Cross coefficient is equals to 1.

Al	Mainly Recovered Element	Mainly Element in Alloy	Mainly Element Lost
Primary Product	1		
Mainly to Pyrometallurgy		3	
Mainly to Hydrometallurgy			
Mainly to Benign Low Value Products		7	1

A8- Inaccessibility reserve versus accessibility recycling.

Table A-8 Inaccessibility reserve versus accessibility recycling in 1/mt.



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Développement d'un indicateur d'évaluation d'impacts de la consommation des ressources : cas d'application à une extraction des matériaux versus un recyclage.

Résumé : L'augmentation de la consommation de ressources suscite des préoccupations quant à leur disponibilité. Ces dernières années, les organisations nationales et internationales ont défini l'approvisionnement durable des ressources et la mise en place d'une économie circulaire comme des objectifs centraux de leurs stratégies à court et long termes.

Dans ce contexte, différentes approches méthodologiques relevant de l'Analyse du Cycle de Vie (ACV) sont utilisées pour caractériser l'impact de l'épuisement des ressources. Les approches actuelles fournissent néanmoins des visions partielles, car dépendantes de données disponibles limitées, et ne reflètent pas les défis de la société en lien avec cette question des ressources.

La méthode et les facteurs nouvellement développés fournissent une vision plus exhaustive de la disponibilité des ressources et peuvent être utilisés dans des analyses du cycle de vie ou dans des approches d'économie circulaire. Ce travail fut produit en partenariat avec le cd2e et le pôle de compétitivité Team². Il a également été réalisé en collaboration avec le bureau d'études et d'expertise en ACV, Cycleco.

Mots clés : analyse du cycle de vie, indicateur ressource, économie circulaire, éolienne, terre rare, aimant permanent

Development of a new resource consumption impact assessment indicator: applied to extraction of materials versus recycling.

Summary: Increase in resource demand raises concerns over their availability. In the recent years, national and international institutions have targeted sustainable resource supply and new economy models (e.g. circular economy, etc.) as a goal of their short- and long-term strategies.

In this context, different methodological approaches under Life Cycle Assessment (LCA) framework are used to address the impact of resource depletion. However, they provide partial visions, based on limited available data, and do not reflect society challenges related to the resources.

The newly developed factors and the LCIA method provide a more exhaustive vision through the availability of resources and may be used in Life Cycle Assessment or circular economy approaches. This work is done in partnership with the cd2e and Team² cluster. It is also carried out in collaboration with CYCLECO Life Cycle Assessment Experts.

Key words: Life Cycle Assessment, Global Resource Indicator, Circular Economy, Wind turbine, Rare Earth Element, Permanent magnet